11th International DAAAM Baltic Conference
"INDUSTRIAL ENGINEERING"
20-22 April 2016, Tallinn, Estonia

LASER CUTTING OF DRY CARBON FIBER

Luthada, P.; Goletic, E.; Ala Puig, O.; Shah, V.; Tai, Q.; Kiviluoma, P.; Korhonen, A.; Partanen, J.; & Kuosmanen, P.

Abstract: *Carbon Fiber Reinforced Plastics (CFRP) are getting increasingly used for building light and strong structures. Most CFRP manufacturing of small parts is done manually, exposing laborers to carcinogenic epoxy and also causing inconsistent quality. This problem can be addressed by a compact automated CFRP part manufacturing machine that is capable of laying dry carbon fiber tape, impregnating and cutting. This paper focuses on evaluating the feasibility and optimization of cutting the tape using a small laser diode system. The testing was carried out on a test jig and using two cutting methods: stationary laser line and moving laser point. Future implementation and possibility of improvements in the system are discussed.*
Key words: automated tape laying, composite manufacturing, tape laying head, additive manufacturing

1. INTRODUCTION

Carbon fiber reinforced plastic (CFRP) parts are increasingly used in automotive and aerospace industries due to their lightweight and high strength [1-3]. However, due to their high cost and specialized manufacturing processes, they have mainly been restricted to aerospace and high-end automotive industries. The future of manufacturing of lightweight composite structures relies strongly on automation to bring down the overall cost of CFRP parts [4, 5]. Manufacturing of these parts is gradually becoming automated using 5-axis Automated Tape Laying (ATL) machines. These machines lay down pre-impregnated carbon fiber tapes using their tape laying head (TLH). However, most small size parts are usually manufactured manually, which exposes the laborer to carcinogenic epoxy and causes large quality variations [6]. This problem is being addressed by developing a compact Tabletop Automated Tape Laying System (TATLS). To avoid using expensive prepregs, dry fiber tapes are being used. These fibers will be impregnated in situ. Such a system requires a miniature Tape Laying Head (mTLH) which can lay and cut the dry carbon fiber tape. Cutting system for mTLH has to be light and maintenance free.

Traditionally, ultrasonic blades are used for cutting prepregs and dry fibers. However, these cutting systems are bulky, require frequent maintenance and blade replacements after a few thousand cuts [7]. In this paper, a new approach for cutting dry carbon fiber tape using a high power miniature diode laser is explored. There is quite a lot of research on cutting finished CFRP parts using lasers [8-10] but very little literature could be found on cutting of dry fibers using lasers.

The proposed laser cutting system uses a high power laser diode, a collimating lens and a double curvature aspheric lens to make a line laser. These components are mounted on a test jig. To have a simple and reliable system, the test was designed to work in a stationary manner, i.e. no moving parts during the cutting process. An alternative method with a relative movement between the laser beam and the fiber tape was also thought of, should the stationary system not be sufficient. The purpose of the system is to cut the carbon fiber tape. Tests were performed to check the feasibility of cutting with different laser and lens configurations. The result is a set of optimal parameters to produce a full clean cut. Based on the results, implementation of laser assisted cutting system in mTLH is discussed here; and possible future improvements in the research and system are presented.

2. METHOD

In this research, the feasibility of a miniaturized laser tape cutting system for mTLH is evaluated. In the experiment, high power laser diode (>6 Watt) was used. The beam created in the diode was passed through a collimating lens first, and the collimated beam was passed through a double curvature aspheric lens (Fan angle 30°) to achieve a line beam with uniform energy distribution. The projected line was directed on to test pieces: 80 g/m^2 paper for geometrical calibration, and single layer, 0.04 mm thick, unidirectional (UD) dry carbon fiber tape. An alternative method was also prepared, in case the resulting line beam was not powerful enough to achieve a successful cut, by adding one controlled degree of movement to the system (relative linear movement beam – test piece). Different power levels, lens arrangements and exposure times were tested for optimizing the system. The goal of this research is to achieve a cutting process that is suitable for TATLS and produces a minimal heat affected zone (HAZ).

The hypothesis was that it is feasible to cut a single-layer tape of dry carbon fiber using the aforementioned system. To validate that hypothesis, a field test was conducted using an Epilog CO2 laser cutter[[11]], with low horizontal speed (2 mm/sec) and low power level (12.5 W) on 3K carbon fiber tow. The test was successful since the laser was able to cut the fiber. This test did not represent the actual experiment setup, but it provided the confidence needed to move forward with experiment.

3. SYSTEM DESIGN

In order to achieve the optimum cutting by laser, distances between laser diode and lenses need to be adjusted. A test jig was built with independently variable geometrical parameters (Fig. 1 & 2). Geometrical parameters allowed to obtain focusing and transformation of the laser beam into a thin line of the smallest thickness possible. Apart from the geometry parameters, the process parameters (power and time period) had to be modifiable too. The test pieces used were a single-layer 10mm wide carbon fiber tape, though they would vary slightly in width and thickness, and the system had to be able to adjust to that too.

The purpose-built system (Table 1) and system parameters (Table 2) consisted of the following components:

Component	Details
1. Laser Diode	Model: NUBM44 Wavelength: 450 nm (blue) Max Output: 6+W Mount - Pitch 0.7 mm (M4)
2. Collimating Lens	Type: G2; EFL: 4.02 mm; SD: 5.3 mm; CA: a-4.80 mm b-3.5 mm; Coating: 400-700 nm; R<=1.0% mount - Pitch 0.5 (M9)
3. Line Generating Lens	Double curvature aspheric (Powell lens), Fan angle: 30 degrees, Uniformly distributed output beam, D 9 mm; Height 13 mm, mount - Pitch 0,7 mm (M4)
4. Jig / Structure	4 degrees of freedom (vertical movement and rotation of laser assembly, vertical movement and rotation of line gen. lens)
5. Carbon Fiber Tape	Textreme UD CFRP tape (ref)
- Power Source	24 W (24 V, 3 A)
- Driver	4.5 A Super X-Drive Bucking type; Soft Start, Overshoot protection, Low Noise, Self-bleeding

Table 1. System components

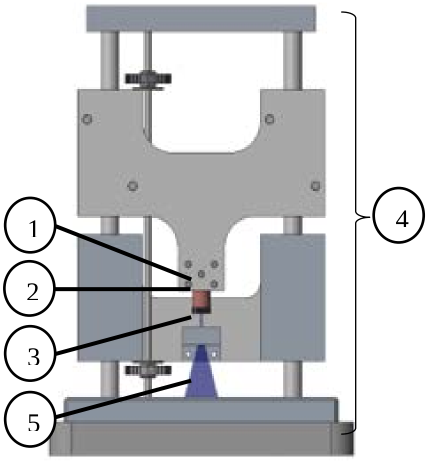

Fig. 1. System design (labelling as per Table 1)

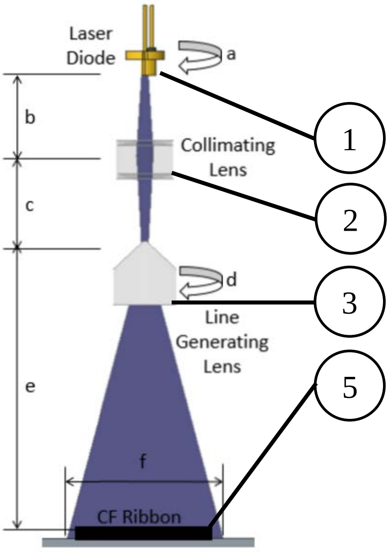

Fig. 2. System design detail

a	Angle Laser Diode
b	Distance Laser Diode (bottom)– Collimating Lens (top)
c	Distance Collimating Lens (top) – Line Gen. Lens (top)
d	Angle Line Gen. Lens
e	Distance Line Gen. Lens (top) – test piece (top)
f	Laser line beam width
-	Power input P(voltage, current)
-	Exposure time

Table 2. System Parameters

4. TEST PROCESS

The tests were performed by directing the beam first onto 80 g/m^2 copy paper (white paper for phase 1 , black for phase 2) and finally onto 0.040 mm thick carbon fiber tape. Changes in the geometrical parameters were made at small increments and analyzed after each change. Power and time parameters were kept constant for each test phase. The size of the resulting burnt hole, line or mark was observed and measured with microscope. The starting point for the geometrical parameters was calculated based on the available information from each of the components. With those, a fairly well collimated beam was achieved. The geometrical parameters were then optimized in the following steps. Firstly, a focused circular point was obtained by adjusting b (phase 1), coarse and fine calibration results are given in Tables 3 & 4 and 5 & 6 respectively.

Voltage	Current	Time	Test piece
5 V	1 A	5 sec	paper, white

Table 3. Constant parameters (Phase 1: Coarse beam calibration)

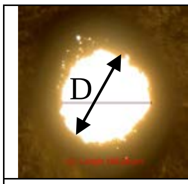	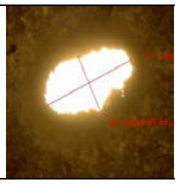	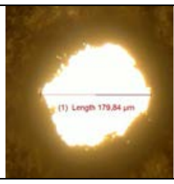
at (b-1/16) mm	at b mm	at (b+1/16) mm
D 580 µm	D_1 610 µm; D_2 380 µm	D 720 µm

Table 4. Burned hole in paper pictures at optimal distance (b) and their measured diameters (Phase 1: Coarse beam calibration)

Voltage	Current	Time	Test piece
5,7 V	2 A	3 sec	paper, white

Table 5. Constant parameters (Phase 1: Fine beam calibration)

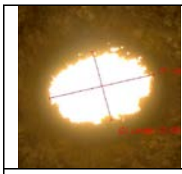	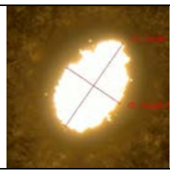	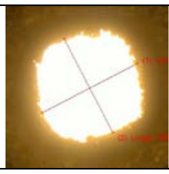
at (b-1/32) mm	at b mm	at (b+1/32) mm
D_1 720 µm; D_2 490 µm	D_1 680 µm; D_2 430 µm	D_1 740 µm; D_2 730 µm

Table 6. Optimal distance (b) (Phase 1: Fine beam calibration)

At this stage, a focused slightly elliptical beam, with its long axis of the ellipsis oriented perpendicular to the fiber direction, was achieved. In the next step, the beam was converted into a focused line by introducing the double aspherical lens and adjusting e and c while f was kept at 10±1mm (Phase 2). The process parameters and achieved cut profile are shown in table 7 and 8 respectively.

Voltage	Current	Time	Test piece
5,7 V	2 A	3 sec	paper, black

Table 7. Constant parameters (Phase 2: Line calibration)

		
at (c-0.7/16) mm	at c mm	at (c+0.7/16) mm
Width: 465 µm	Width: 375 µm	Width: 375 µm

Table 8. Cut on the paper during phase 2: Line calibration

The results from this phase were satisfactory and parameters were obtained (Table 8) for consistent, through cutting of the paper test pieces.

a	Angle Laser Diode	90° to fiber direction
b	Distance Laser Diode (bottom) – Collimating Lens (top)	2.50 mm
c	Distance Collimating Lens (top) – Line Gen. Lens (top)	Not affecting focus, just width of line
d	Angle Line Gen. Lens	0° to larger diameter of elliptical beam
c+e	Distance Collimating Lens (top) – Test piece (top)	54.50 mm
e	Distance Line Gen. Lens (top) – test piece (top)	20.83 mm
f	Laser line beam width	10.00 mm

Table 8. Optimal Geometrical Parameters for Line Generation

With the focused line, with almost homogeneous power distribution, the next step (Phase 3) was to calibrate the process parameters, namely power (voltage and current) and time. The test pieces for this phase were 10 mm wide pieces of unidirectional carbon fiber tape, with the fibers perpendicular to the laser line, held flat using tape on both ends. Starting from the threshold levels, the input power was gradually increased until the maximum deliverable from the power source and the driver were reached. The operation was not successful in obtaining a cut of the carbon fiber tape, even with the highest power input.

The laser line generated with the used setup was not able to cut through the tape wider than 5mm less than that width was possible, but the results were inconsistent and would be too far from the intended purpose to be useful. The apparent reason was that the beam did not have enough power to heat up the carbon fiber to a high enough temperature, regardless of how long time it was exposed to the beam (Fig. 3). The high thermal conductivity of the carbon fiber made it impossible with the used setup to reach burning temperature with a laser line.

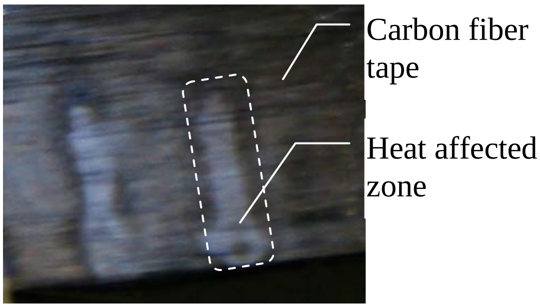

Fig. 3. Phase 3 test, Heat affected zone

Therefore, the alternative method (Phase 4) had to be tested, using relative movement between laser beam (Table 9) and test pieces, instead of the line generating lens. In particular, a controlled linear movement of the test piece, perpendicular to the laser beam, which was stationary and focused to a point.

Using the calibration results from Phase 1, and adding a controlled linear displacement to the tape in a direction perpendicular to the fibers, the tape could be cut in a consistent manner, with minimal heat affected zone(Fig. 4), in 20 seconds. The full clean cut can be observed in Fig. 5.

Voltage	Current	Time	Test piece
12 V	2 A	20 sec	Carbon fiber tape 20 mm wide, 0.040 mm thick

Table 9. Constant parameters (Phase 4)

5. RESULTS

Focus to Point: Successful focusing of the beam to a point (ellipsis) with the larger diameter of 680 µm capable to burn through the paper test piece.
Focus to Line: Successful focusing of the beam to a line with the widest width under 300 µm, capable to burn through the paper test piece.
Cut Carbon Fiber Tape with Line: Unsuccessful cutting thoroughly carbon fiber tape any wider than 5mm, with the maximum achievable power setting allowed by the experimental setup used.

a	Angle Laser Diode	90° to fiber direction
b	Distance Laser Diode (bottom) – Collimating Lens (top)	2.50 mm
c	Distance Collimating Lens (top) – Line Gen. Lens (top)	Not affecting focus, just width of line
d	Angle Line Gen. Lens	0° to larger diameter of elliptical beam
c+e	Distance Collimating Lens (top) – Test piece (top)	54.50 mm
-	use of double curvature aspherical lens	No
-	use of Relative movement beam- test piece	Yes
-	Relative Velocity	1 mm/s
-	Exposure Time	20 seconds
-	Power input P(voltage, current)	24 W (12 V, 2 A)
-	Laser Beam Power output	could not be measured

Table 10. Optimal System Parameters

The optimal parameters to successfully perform the objective cutting operation are shown in Table 10.
Cut Carbon Fiber Tape with moving Point: Successful cutting thoroughly carbon fiber tape, with minimal HAZ (Fig. 4).

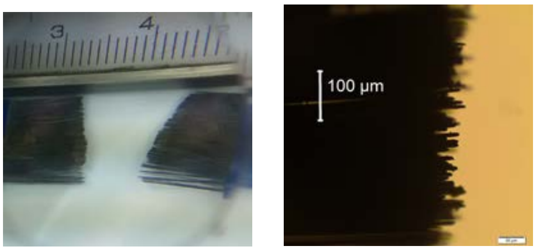

Fig. 4 Heat affected zone in cut fiber (left) and Full clean cut in Phase 4 (right)

6. CONCLUSION AND DISCUSSION

The experimental testing showed that the setup used was not able to cut through the carbon fiber tape using a stationary laser line method, due to having a power peak too small to heat up the fibers enough for them to reach burning temperature. A different selection of components that could be focused to a smaller size would be likely to achieve high enough power density when distributed to a wide line; however the system used did not allow for such precision levels. Alternatively, the results also show that using a more powerful laser could easily perform the task. Substituting the line generation lens for a relative moment beam-tape, the cutting operation was successful.
The chosen method, was the simplest solution that fitted the final purpose that this research was done for: simple miniaturized system to cut dry carbon fiber for a tape laying machine (TATLS). This alternative meant adding one degree of freedom to the system. However this could be executed with minimal alterations in the design, and offered a clean and consistent cut of the tape, making it an affordable compromise and allowing the development to move forward.

7. REFERENCES

1. Mills, A., *Automation of carbon fibre preform manufacture for affordable aerospace applications.* Composites Part A: Applied Science and Manufacturing, 2001. **32**(7): p. 955-962.
2. Wisbey, J.D., *Multi-tow fiber placement machine with full band width clamp, cut, and restart capability*. 1990, Google Patents.
3. M, V.M., *United States Patent: 5110395*. 2016.
4. Prüß, H. and T. Vietor, *Design for fiber-reinforced additive manufacturing.* Journal of Mechanical Design, 2015. **137**(11): p. 111409.
5. *COMBINING ADDITIVE MANUFACTURING WITH CFRP COMPOSITES: DESIGN POTENTIALS.* 2016.
6. Subramanian, P., *Safety Management for advanced composites.* 2011.
7. *Composite Materials - Science and Engineering | Krishan K. Chawla | Springer*. 2016.
8. Cenna, A.A. and P. Mathew, *Analysis and prediction of laser cutting parameters of fibre reinforced plastics (FRP) composite materials.* International Journal of Machine Tools and Manufacture, 2002. **42**(1): p. 105-113.
9. Pagano, N., et al., *Laser Interaction with Carbon Fibre Reinforced Polymers.* Procedia CIRP, 2015. **33**: p. 423-427.
10. Stock, J., M.F. Zaeh, and M. Conrad, *Remote Laser Cutting of CFRP: Improvements in the Cut Surface.* Physics Procedia, 2012. **39**: p. 161-170.
11. *The Epilog Laser Fusion 75 W*. 2016.

8. CORRESPONDING ADDRESS

Panu Kiviluoma, D.Sc. (Tech.), Senior University Lecturer
Aalto University School of Engineering
Department of Mechanical Engineering
P.O.Box 14100, 00076 Aalto, Finland
Phone: +358504338661
E-mail: panu.kiviluoma@aalto.fi
http://edp.aalto.fi/en/

ADDITIONAL DATA ABOUT AUTHORS

Luthada, Pravin
E-mail: pravin.luthada@aalto.fi

Goletic, Emir.
E-mail: emir.goletic@aalto.fi

Ala Puig, Oriol
Email:oriol.alapuig@aalto.fi

Shah, Vaibhav
E-mail: vaibhav.shah@aalto.fi

Tai, Qiongge
E-mail: qiongge.tai@aalto.fi

Jouni Partanen, Phd (Tech.), Professor
jouni.partanen@aalto.fi
+358 50 5769 804

Kuosmanen, Petri, D.Sc. (Tech.), Professor
Phone: +358 500 448 481
E-mail: petri.kuosmanen@aalto.fi