



# Laser cutting of carbon fiber reinforced plastic components for remanufacturing

Farhan Arshed<sup>1</sup> · Abdul Ahmad<sup>1</sup> · Paul Xirouchakis<sup>1</sup> · Ioannis Metsios<sup>2</sup>

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## Abstract

Carbon fiber reinforced plastic (CFRP) is extensively used in automotive and aerospace industries with the aim to achieve reduction on emissions by reducing weight. Due to governmental regulations to reduce the environmental impact and to reduce waste, the need for remanufacturing CFRP is becoming an interesting area of application with economic benefits to industry. This is important as manufacturing carbon fiber is a costly process and remanufacturing CFRP is more cost effective and reduces the dependency on virgin materials. Processing CFRP to meet demands, for fast and high-quality cuts, can impose problems for conventional methods. The use of multi-pass scanning technique in laser cutting CFRP is investigated using a 1.5 kW fiber laser with assist gas pressure of 16 bar and gas flow rate of 126 lt/min. Using multi-pass technique, a through cut can be obtained by repeating the beam travel more than once. The advantage of laser cutting when compared with traditional CNC, is the low cost of maintenance over time due to the non-contact nature of the process i.e. no wear of tool at contact area. And due to the small beam spot size of the laser small and complex shapes can be cut. The aim of the paper is to determine how the process performs in terms of cutting speed and fiber damage. Average power was used to carried out experimental tests. A fiber damage below 100  $\mu\text{m}$  with laser cutting speed of 2.5 m/min and above was obtained. Thermal effects were analyzed using scanning electron microscope (SEM) and optical microscope (OM). The fiber damage was further optimized using specialist methods such as double aperture nozzle and trenching. The use of trenching and double aperture further reduces the fiber damage to 10  $\mu\text{m}$  and 50  $\mu\text{m}$ , respectively with laser cutting speed of 7.5 m/min and 3.33 m/min.

**Keywords** Carbon fiber reinforced plastic · Fiber damage · Laser cutting · Optimization · Fiber laser · Remanufacturing

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✉ Farhan Arshed  
farhan.arshed.100@strath.ac.uk

<sup>1</sup> Design, Manufacture & Engineering Management, University of Strathclyde, Glasgow, UK

<sup>2</sup> Lumpi Ltd, Kemp House, London, UK

## Introduction

Due to its superior mechanical properties, carbon fiber reinforced plastic (CFRP) has materialized as a replacement for existing materials used in aerospace, automotive, building, turbine, and high-grade sports equipment. CFRP is lightweight with high strength, high hardness, and good resistance to breaking and low thermal expansion. In the automotive industry, the aim of lighter and more energy efficient vehicles with high performance and fuel economy and lower CO<sub>2</sub> emissions, CFRP played a fundamental role. It is estimated that the replacement of metal components with composite materials will have a weight saving up to 30 – 40% and cost saving of 30 – 50% at the same time [31]. This implies that remanufacturing of CFRP becomes of paramount importance in safeguarding the environmental benefits of using composite material. Remanufacturing of CFRP using laser cutting also reduces the waste and helps to achieve net zero waste target when compared with other methods of CFRP machining such as water jet and mechanical cutting. If there is a damage in the middle of the CFRP sample, removing damage using mechanically or water jet cutting will lead to tool wear, delamination, and moisture penetration into the fibers, whereas, if lasers are used, a damaged part can easily be removed, and sample can easily be remanufactured to original equipment manufacturer specifications. Proper machining technology must be used in order to use CFRP in various industries. But, due to its heterogenous structure, conventional machining such as drilling, milling, sawing and abrasive water jet cutting has major disadvantages such as fiber delamination, pull-out, interior cracks, tool wear, moisture uptake which leads to degradation of mechanical properties as moisturized polymers became softer and aggravate fiber-matrix adhesion [27]. Laser cutting is a non-contact process without any tool wear and cutting force and can cut tight angles with narrower kerf width.<sup>1</sup> Lasers also benefited from their capability of being transmitted through fiber optic, robot manipulation and automation. The challenging aspect of laser processing is to reduce thermal damage and maintaining high processing speed. Large heat affected zone (HAZ), charring, resin recession and delamination are some of the quality defects, which are major obstacles for industrial applications of laser machining of CFRP composites. Based on previous research, this study used a single mode fiber laser to meet the industrial demands of high rate of cutting speed and low fiber damage (HAZ). The laser cutting experiments investigated the effects of cutting speed, number of passes, nozzle diameter from the cut surface, nozzle diameter, double aperture and trenching on the extent of fiber damage. Double aperture and trenching are novel technique used to improve the state of the art for both fiber damage extent and cutting speed.

## Research justification

Conventional methods for cutting cause high tool wear of the machining heads, CFRP delamination and fiber pull out [33]. Cutting techniques such as water jet (WJ) and abrasive water jet (AWJ) have several advantages such as increased cutting speed, reduced thermal stress and omission of dust by water jet [1], however water could cause moisture build up at the surface or cause delamination due to high velocity impact [28]. Osmotic erosion can also occur, and this is a process in which water penetrates the material and causes

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<sup>1</sup> Width of material removed by laser cutting process.

degradation as investigated by [35]. These methods have failed to cut small or complex shapes due to tool size and dimensions [1].

Other methods used for cutting CFRP are electro discharge machining (EDM) or wire electro discharge machining (WEDM) [14]. Both EDM and WEDM are capable of cutting small and complex shapes with accurate dimensions and surface finish. Habib et al. [8] identified that material removal not only depends on process parameters but also on tool path and fiber direction. The high current density that is used in the EDM and WEDM processes can cause melting of the polymer at the cut surface thus increases the HAZ extent at the cut surface. To reduce disproportionate melting of the cut surface, low current density is required, but at low current density, the material removal rate (MRR) is very low typically 2 – 5 mm<sup>3</sup>/min. There is a direct correlation between low MMR and slow cutting speed. For example, an MMR of 4 mm<sup>3</sup>/min for a 2 mm thick CFRP sample and 0.1 mm wide eroded trench would correspond to 20 mm/min cutting speed [8].

Abrate and Walton [1] suggested an alternative to traditional processes and that is laser cutting which does not involve mechanical forces and tool wear. Due to its small beam spot size complex shapes can be cut. Laser cutting is predominantly driven by a thermal process based on interaction between the laser beam and the material that causes ablation, i.e. the temperature locally exceeds the vaporization temperature of the material [1]. HAZ occurs around the ablated region defined as a one in which the material properties have been modified by the heat dissipated during the process. The HAZ could be reduced by adjusting laser processing speed, environmental factors such as humidity and temperature, type of assist gas, focusing lens, beam divergence and energy distribution profile, properties of pulse (energy, repetition rate, duration) type of matrix and its texture, material thickness, thermal conductivity and surface reflectivity are among some of the factors as reported by Mathew et al. [19]. Takahashi et al. [32] and Xu et al. [38] investigated the impact of laser wavelength on the cut quality by comparing infrared (IR) and ultraviolet (UV) lasers. Most polymer matrices are highly transparent to near infrared radiation of wavelengths around 1000 nm with absorptivity less than 15%, whereas carbon fiber has 80% absorptivity [21]. Consequently, the bulk of the IR laser beam energy passes straight through the resin matrix and heats the carbon fibers directly. Therefore, laser energy is mainly absorbed by carbon fibers. This causes the matrix to be heated indirectly by hot carbon fibers and not by laser light. UV lasers perform much better than IR lasers in this aspect because both polymer and fibers absorb UV light very well which provides the outer shell electrons with enough energy to allow them to escape the organic polymer molecule or to break certain covalent bonds depending on photon energy. This disintegrates polymers faster and more efficiently than heat and promotes evaporation at the same time. Evaporation or ablation whether it has originated from thermal transition beyond gas point or molecular dissociation, contributes to reducing HAZ as the energy absorbed is conveyed away by the gas nozzle, rather than getting trapped in the material and dissipating inside it. Hence, UV radiation provides more consistent processing quality than NIR. Middle or far IR laser radiation can interact well with all polymers, but the dissociation action of UV laser has an extra advantage to absorption. However, high power UV lasers are currently not available and therefore composite materials cannot be cut at industrial speeds.

Additionally, to laser wavelength another parametric selection of lasers is continuous wave (CW) and pulsed wave (PW) emission, resulting in two distinct types of laser sources which can be used in laser cutting. Small HAZ could be achieved by pulsed laser emission due to the very small irradiating time per one pulse and cooling time between pulses [26]. However, the processing speed is typically slower than CW laser due to its low average power available by pulsed industrial sources in comparison to CW. This persisting fact

about industrial laser sources leads to low output according to Fujita et al. [5]. Weber et al. [37] determined that maximum cutting speed is influenced by average power by modelling CFRP cutting process with the help of 1–D thermal analysis. Matrix damage extent is typically dependent upon temporal beam intensity, which, can be increased by increasing the average laser power, releasing laser energy in few and shorter pulses or by optically reducing the focus spot size. Weber et al. [37] concluded that by reducing the laser spot size, the processing depth reduced. If the peak power is reduced by decreasing pulse duration, it reduces the average power and energy per pulse.

Herzog et al. [9] used pulsed Nd:YAG (Neodymium – doped Yttrium Aluminum Garnet) laser with pulse duration between 0.5 ms to 50 ms, CW Disk, and quasi – CW CO<sub>2</sub> laser to investigate cut qualities. Herzog et al. [9] concluded that smallest HAZ was generated by Nd:YAG laser. For Nd:YAG pulsed laser, HAZ achieved was 0.6 mm, for Nd:YAG it was 1.2 mm and for CO<sub>2</sub> laser HAZ was 1.4 mm. As for optimized cutting speeds, for a 1.5 mm thick specimen pulsed Nd:YAG, CO<sub>2</sub> and disk laser cutting achieved speeds of 0.1 m/min, 0.1 m/min and 1.5 m/min, respectively.

Freitag et al. [4] suggested that by using low repetition rate and high pulse energy at same average power, HAZ could be minimized. Leone et al. [17] investigated laser cutting using Yb:YAG (Ytterbium – doped Yttrium Aluminum Garnet) pulsed laser by using quality factors of cut samples such as HAZ and kerf width and concluded that quality of cuts was improved by employing the multi pass technique with increased scanning speed. The cutting speed with selected parameters varies between 0.3 – 0.7 m/min. Leone and Genna [15] investigated experimentally to analyze the impact of processing parameters on kerf edge, HAZ and cutting region using Yb:YAG laser. They concluded that the cutting speed, kerf width and HAZ are impacted by pulse energy, which is energy release per unit area at a certain linear transverse speed, and cooling effect. They also concluded by using a multi pass scan technique the HAZ and kerf geometry could be reduced and improved, respectively. Also, the scanning speed and direction of fibers affect the kerf width and HAZ. The cutting speed of 0.6 m/min was obtained, but it depends upon tuned process parameters such as average power, pulse frequency and pulse duration. This is also true for HAZ of 170 – 160  $\mu$ m for 1 mm thick laminate.

In comparison to pulsed systems with limited average power due to the complexity of their architecture, a CW laser with high power could be used to obtain higher processing speeds to meet industrial demands. CW lasers are susceptible to generate larger HAZ than pulsed laser. This can be minimized by using multi-pass technique and higher laser scanning speed as investigated by Niino [20]. Goeke and Emmelmann [7] use Yb-doped fiber laser to investigate laser cutting and concluded that both HAZ and kerf width reduced considerably when scanning speed is increased. The HAZ extent for fiber laser with wavelength of 1.07  $\mu$ m was between 440–550  $\mu$ m, whereas, for CO<sub>2</sub> slab laser with wavelength of 10.6  $\mu$ m it was between 300–350  $\mu$ m on 1 mm thick CFRP sample. This may be attributable to the higher feed rate of CO<sub>2</sub> laser or the markedly higher absorption of the CO<sub>2</sub> laser wavelength by polymer and organic materials such as carbon fibers, resulting in faster ablation and convection of residual energy away from the processed area in comparison to the moderate absorption of Yb-fiber radiation by polymers. Klotzbach et al. [13] also confirmed that HAZ is narrowed significantly with increased laser scanning speed and by multi-pass. Bluemel et al. [3] used 6 kW fiber laser to study the impact of processing speed on HAZ width and they concluded that as velocity increased HAZ reduced. Also, the higher laser power allowed higher scanning speed which results in smaller HAZ. Jung et al. [12] used 16 kW disk laser to investigate laser cutting at high speed and achieved the best quality

and smallest HAZ. Additionally, the dwell time of 1 s between the passes is optimal to reduce thermal effects such as HAZ and kerf width. They concluded that kerf width and HAZ reduced as cutting speed increases, and if laser power increased from 2 to 5 kW it reduces the processing time without having an impact on the cutting quality. It was also demonstrated that laser cut CFRP sample did not degrade mechanically as tensile strength of laser cut CFRP was in good agreement with virgin CFRP samples. Rao et al. [23] investigated laser cutting of CFRP using 400 W fiber laser assessing the effect of laser power, scanning speed and assist gas on quality of cuts. These factors were examined statistically using surface response methodology. They conclude that fiber laser can be used to cut CFRP of 1.4 mm thickness with ideal parameters of laser power of 260 W achieving cutting speed of 4.5 m/min and assist gas flow rate of 14.23 l/min. With these settings, kerf width of 163.71  $\mu\text{m}$  and HAZ of 573.28  $\mu\text{m}$  was experimentally achieved. Riveiro et al. [25] performed laser cutting using CO<sub>2</sub> laser in both CW and pulsed modes. They investigated the impact of processing parameters on kerf, HAZ and quality of cross section. They concluded that using a co-axial subsonic or off-axial supersonic assist gas jet produces cut quality with similar HAZ. However, the tendency of the formation of overhanging fibers is higher with off-axis supersonic jet. If the laser power is reduced to 1.6 kW and the cutting speed is set between 2 m/min and 4 m/min, the excessive thermal stress on the work piece is reduced and better cut quality is obtained. Li et al. [18] used a CW fiber laser to study cut quality and morphology of cut surface using multi-pass and single-pass strategies. The investigation concluded that micro cracks, delamination, holes and overhanging fibers are some of the defects detected during laser cutting of CFRP. The continuous improvement in laser material processing have opened new avenues such as using high-power laser with enhanced beam quality and development of galvanometer scanner systems with quick laser material interaction. In literature, generally CW or pulsed lasers are used for cutting. In pulsed mode, short or ultrashort lasers are utilized with small spot size and adequate cooling between the pulses, and this maintains low HAZ. However, low average power pulsed mode laser the cutting speed is slower than CW laser. At high cutting speeds was achieved using high power CW lasers results in significant HAZ in comparison to pulsed lasers. Multi-pass strategy without dwell time between passes showed limited improvement in terms of HAZ when compared to single pass strategy.

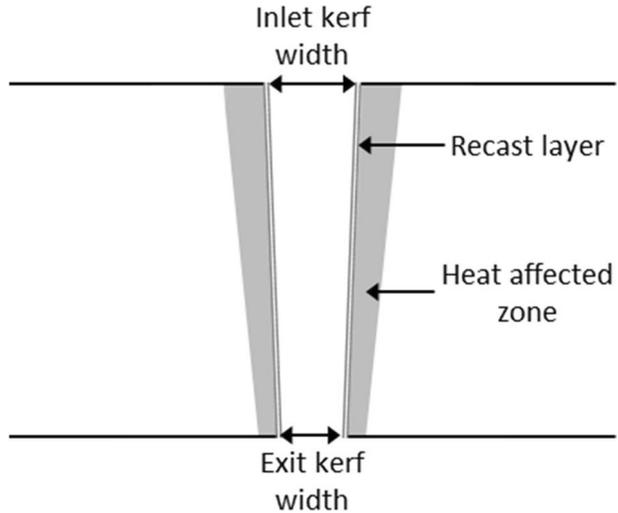
## Contribution to knowledge

Table 1 shows the types of lasers used in the literature with process parameters. Based on previous findings, in this paper a single mode fiber laser was used for laser cutting to meet industrial demands of high rate of cutting and low damage to the fibers. The laser cutting experiments investigated the effects of cutting speed, number of passes, nozzle distance from cut surface, nozzle diameter, double aperture and trenching on the extent of the fiber damage, to improve state of the art of 100  $\mu\text{m}$  for fiber damage extent and cutting speed of 2.5 m/min. The use of trenching and double aperture technique, which is not investigated in literature, the HAZ achieved was 50  $\mu\text{m}$  and cutting speed of 7.5 m/min. Cutting quality was analyzed using scanning electron microscope (SEM) and optical microscope (OM) observations.

**Table 1** Commonly used industrial laser in composite processing

Type of laser	Fiber laser	Q Switched pulsed laser	CO <sub>2</sub> Laser CW	CO <sub>2</sub> Laser pulsed	Pulsed Nd:YAG	Trumpf Tru disk 6001	Yt:YAG fiber laser	Trumpf single mode fiber laser
Wavelength (nm)	1070	1064	10,600	10,600	1064	1030	1075.6	1070
Pulse rate	N/A	N/A	N/A	N/A	0.5 ms	30 ns	N/A	N/A
Frequency	N/A	30 – 80 kHz	CW	2 – 5 kHz	35 – 45 kHz	5 – 18.8 kHz	N/A	5 kHz
HAZ	573 μm	0.1 mm	540 μm	540 μm	N/A	N/A	139 μm	N/A
Sample thickness	1.5 mm	0.5 mm	3 mm	3 mm	1.5 mm	1.5 mm	1.4 mm	1.5 mm
Average power (W)	400	30	600	1000–1600	300	1500	30,000	1500
Fiber diameter	N/A	100 μm	N/A	N/A	N/A	400 – 600 μm	300 μm	20 μm
Reference	[23]	[17]	[24]	[24]	[34]	[36]	[10]	[30]

**Fig. 1** Material characteristics caused by laser cutting



## Laser cutting methodology

A high-quality cut can be sought with the use of laser cutting because of the control of processing parameters available by laser systems. Some of the key factors that have an impact on laser cutting of composites are speed of cutting, distance between cutting head and work piece, scanning speed, number of passes, diameter of gas nozzle and presence of cooling assist gas [2].

Laser cutting, if not optimized based on the above factors, can have a significant impact on the material and its strength i.e. damaging the internal structure of the composite and creating large HAZ and the formation of an inadequate kerf taper [29]. Also, laser cutting causes the production of precarious fiber powder, organic compounds and CO and CO<sub>2</sub> at high concentrations. Therefore, laser cutting must be carried out in controlled environments [26].

## Laser material removal

During laser cutting, the laser beam is intended to remove the material and cause the local surface to heat up and due to this reaction different phases can occur and produce a recast layer as shown in Fig. 1.

Furthermore, optical energy is absorbed by the workpiece when the beam strikes the surface. A large proportion of this absorbed energy is converted to locally dispersed thermal energy, heating the material under the beam to very high temperatures. In metals, the workpiece is transformed into molten state from the absorbed energy. The molten material is removed, with help of assist gas, with kerf formed up to certain depth. The kerf is empirically expected to form at lower densities around  $10^2$ – $10^3$  W/cm<sup>2</sup> in composites and  $10^6$  W/cm<sup>2</sup> in metals. Metals will reach molten state and then evaporate or subjected to metal shearing. The polymer matrix in a composite to some extent behaves in a similar manner. It can also degrade under the irradiation and plasma conditions. The carbon fibers may require higher beam density than that of metals [16]. At the kerf edge the process of material is caused by scribing, melt shearing using reactive gas, chemical degradation and

**Table 2** 2 mm CFRP fabric layout

Layer	Fiber description
1	150 gsm 0 <sup>0</sup> /90 <sup>0</sup> 12 k standard modulus carbon
2	148 gsm +45 <sup>0</sup> /-45 <sup>0</sup> 12 k standard modulus carbon
3	148 gsm +45 <sup>0</sup> /-45 <sup>0</sup> 12 k standard modulus carbon
4	150 gsm 90 <sup>0</sup> /0 <sup>0</sup> 12 k standard modulus carbon
5	150 gsm 0 <sup>0</sup> /90 <sup>0</sup> 12 k standard modulus carbon
6	148 gsm -45 <sup>0</sup> /+45 <sup>0</sup> 12 k standard modulus carbon
7	148 gsm -45 <sup>0</sup> /+45 <sup>0</sup> 12 k standard modulus carbon
8	150 gsm 90 <sup>0</sup> /0 <sup>0</sup> 12 k standard modulus carbon

vaporization [11]. By moving the cutting head, a thin layer of char is formed caused by the subsequent melting and cooling of the material. This damages the work surface and introduces sub-standard cut quality. Therefore, optimization of cutting parameters is required to minimize the fiber damage and char formation [22].

### The workpiece material

The type of CFRP investigated is 12 k standard modulus carbon supplied by INVENT GmbH who are leading manufacturers of CFRP for industries including the automotive and aerospace. The samples used in the experiments were square plate CFRP pieces measuring 100×100 mm inside and 2 mm in thickness and consisted of 8 thin layers of CFRP fabric. The fabric layout is detailed in Table 2. The matrix type used in the material is medium viscosity epoxy resin. The resin used in the sample has three components, a resin itself which is a medium viscous epoxy resin, curing agent which is also a low viscous very fast amine hardener and an additive which is a silicon and wax free internal mold release agent is designed to use in mass production of structural automotive parts such as frame, chassis, and floor panels.

The definitions of the measurements used to assess the quality of the laser cuts are:

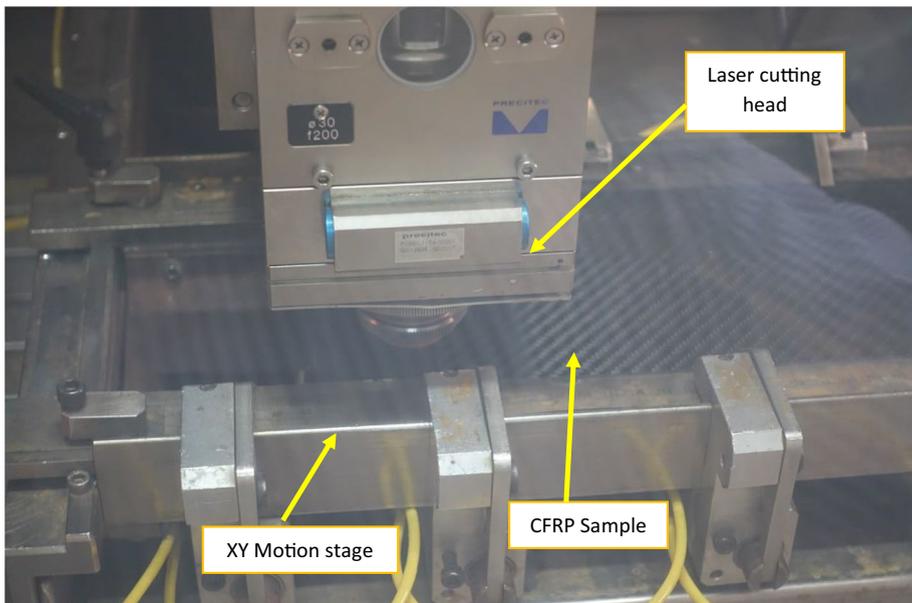
- **Fiber damage extent** – The extent of fibers broken individually or in batched of 2 to 5. Loose fibers are not counted as broken.
- **Epoxy removal** – Removal of top sealing layer epoxy resin from edge of the cut measured on the irradiated side looking onto the edge of the cut.
- **Top delamination** – Thickness and depth of the layer which detached from the bulk material, measured on the irradiated side looking onto the edge of the cut.
- **Bottom delamination** – Thickness and depth of the layer which detached from the bulk material, measured on the side of beam exit looking onto the edge of the cut.

### Experimental setup

Initial tests were carried out using a 2 kW fiber laser [21]. A total of 84 tests sets were performed (12 for each technique). Initial results indicated that the cutting speed achieved was 3.5 m/min, however the fiber damage extent was 300 μm. second trials were performed using a 50 W Nd:YAG laser [17]. Test results shows that cutting speed was very low (0.05 m/min), however, fiber damage extent was below state of the art. Tests sets were

**Table 3** Characteristics of the SP-1500-CW-025–10-PQA laser

Parameter	Value	Unit
Average power	1500	W
Wavelength	$1080 \pm 2$	nm
Rise time	10	$\mu$ s
$M^2$	1.3	
Beam divergence	82	mrad full cycle
Fiber diameter	25	$\mu$ m
Spot size	28	$\mu$ m

**Fig. 2** Focusing optics system placed over a sample

conducted to examine the effects of cutting speed, multi-pass, stand-off distance, large nozzle aperture diameter, nozzle double aperture and trenching for straight line cuts used by [6, 17, 21]. For the experiments, a diode pumped single mode fiber laser by SPI Lasers was used with its characteristics shown in Table 3.

A laser processing station containing XY motion stage of two degrees of freedom was used for beam delivery. The processing station has a laser protective viewing window Fig. 2. The fiber was attached in a parallel and refocusing optical system with 1:1 demagnification ratio which can be adjusted in height and has a focal length of 200 mm. The optical system can also be adjusted manually for focusing optics thus affecting focal position. The purge gas jet nozzle and the rest of the focusing optic mechanics were also manually adjustable. An exchangeable gas jet nozzle of different apertures was used, and argon process gas was delivered coaxially with the beam. Single and double aperture were the two types of nozzles used in the experiments. Double aperture nozzle was used to deliver a more collimated gas jet for deeper cuts.

**Table 4** Experimental conditions

	No of tests	Stand-off Z (mm)	Noz- zle gap (mm)	Linear Speed (m/ min)	Nozzle diameter (mm)	No of passes
Multi-pass	12	0	1.0	5 – 10	1.0	2 – 3
Stand-off Z	12	-1—2	1.0	2.5	1.0	1 – 3
Nozzle diameter	12	1.3	1.0	2.5—12	2.0	1 – 3
Trenching	12	1.3	1.0	7.5—15	1—2	1
Trenching + Double aperture	12	1.3	1.0	7.5	2.0,1.5	1
Double aperture	12	1.3	1.0	2.5 – 10	2.0,1.5	1 – 3
Verification	12	1.3	1.0	2.5—10	1.0	3

For microscopic analysis, a 10×magnification eyeloop with 100 μm graduation reticule, 60 to 100×magnification compact microscope with 10 μm graduation reticule, and 50×magnification USB microscope with 50 μm graduation reticule were used. A field emission analysis was carried out by scanning electron microscope (SEM). For thermal imaging of the process, a Flir digital thermal imaging camera with recording capability of 320×240 pixels and thermal sensitivity of 0.1 °C with manual focusing was used.

## Experimental procedure

The experiment was carried out using the following process parameters assuming the laser power at 1500 W and gas pressure and gas flow rate kept constant at 16 bar and 126 lt/min. The experiment conditions are shown in Table 4

## Effects of cutting speed

The interaction time is controlled by the cutting speed. the vaporization temperature is higher than resin. Therefore, cutting composite takes time at the expense of fiber damage. In CFRP composites, the fiber with high thermal conductivity transmits the heat through fibers faster than that of matrix, this results in wider fiber damage. Therefore, at higher cutting speed interaction time is shorter, hence, smaller fiber damage.

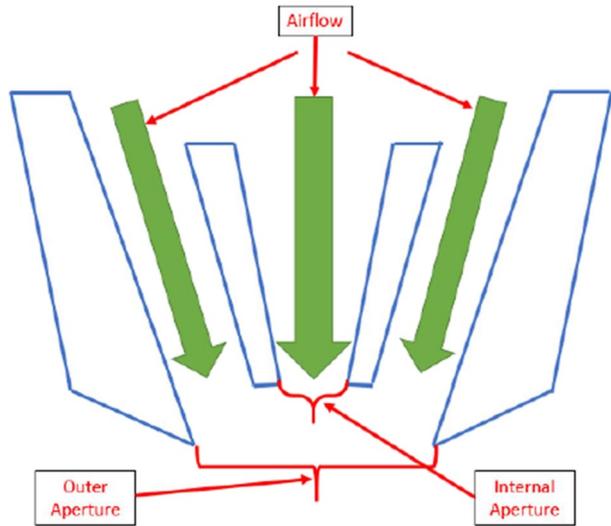
## Multi-pass technique

In multi-pass technique the material is evaporated up to a certain depth per pass by a laser beam. The process is repeated until the full thickness of material is cut. The process speed is defined as a scanning speed multiplied by number of passes. The fiber damage is reduced while using multi-pass as the time between passes allows material to dissipate heat.

## Stand-off distance

The nozzle stand-off distance is critical in laser cutting. This ensures the proper levels of energy density at the sample. The distance also has an impact on the gas flow patterns of the gas which has a direct bearing on cutting performance and cut quality.

**Fig. 3** Schematic of an inductive cross-section of the double aperture nozzle, also showing the direction of air flow



### Large nozzle aperture

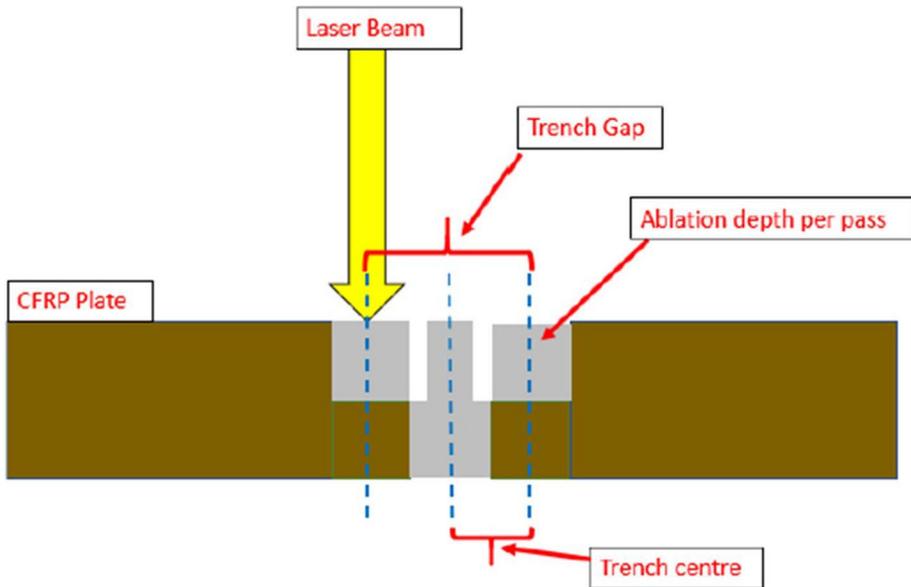
The nozzle delivers the gas to cutting front while making sure that the gas is coaxial with the laser beam and stabilize the pressure on the sample. The nozzle design determines the quality of the cut.

### Double aperture

The double aperture nozzle is similar to single aperture nozzles. The difference in the double aperture is the cone insert has a smaller aperture itself. Radial blades are used to suspend the cone insert, this draws air flow annularly through a large aperture and axially through the center of the smaller aperture. The cross-section schematics of the double aperture is depicted in Fig. 3. Double aperture nozzle was mainly used to cut thicker material by generating a thin flow of air that maintains its size after exiting the nozzle. The double aperture has outer diameter of 2.0 mm and inner diameter of 1.5 mm.

### Trenching

With the use of multi-pass technique, it was noted that measured characteristics are still high. To overcome this issue, an approach to widening the kerf was investigated. Trenching is obtained by traversing three parallel lines beside each other. The purpose is to open a channel or trench which is wider than the channel opens by a single beam. Once trench gap is defined, the center of the beam is placed at either edge of the top surface trench gap which emerges wider than this gap. Once the gap was opened by 2 passes, a beam passes the third time through the center of the trench. This approach



**Fig. 4** Schematic showing the position of the trench cut lines in relation to the kerf / trench center

**Table 5** Summary of averaged measured parameters

Trials	Cutting speed (m/min)	Fiber damage extent ( $\mu\text{m}$ )	Epoxy removal extent ( $\mu\text{m}$ )	Top delamination ( $\mu\text{m}$ )	Bottom delamination ( $\mu\text{m}$ )	No of tests
Multi-pass technique	3.3	89	400	128	60	12
Stand-off distance	2.8	48	312	120	53	12
Large nozzle aperture	3.2	99	283	134	88	12
Trenching	9.4	31	196	135	102	12
Double aperture	3.8	59	157	122	110	12
Effects of cutting speed	2.8	75	396	139	82	12

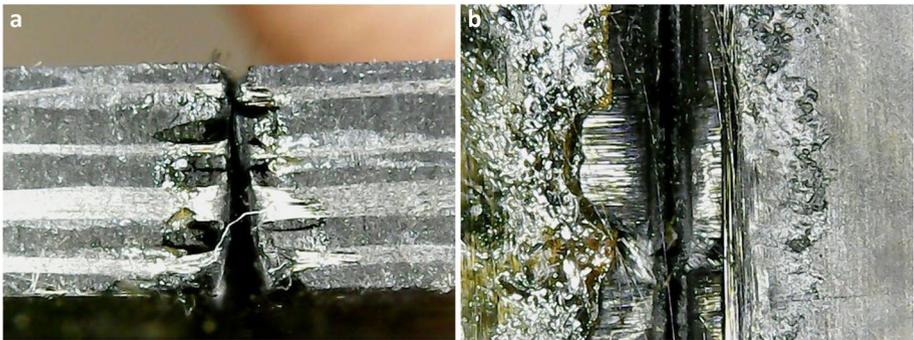
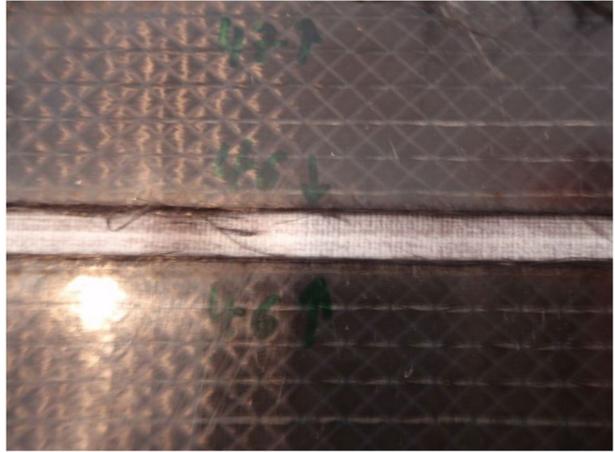
provides better means of entry to the deeper levels of the material without impacting the edges with laser power that may be required to process these levels as shown in Fig. 4.

## Results

### Effect of cutting speed

Several experiments were carried out to examine the effects of cutting speed. The summary of averaged results of the measured parameters are shown in Table 5 with power kept constant at 1.5 kW, number of passes set at 1, nozzle aperture of 1.0 mm and gas pressure

**Fig. 5** Photograph of test cuts at cutting speed of 2.5 m/min



**Fig. 6** Microscopy image of trials using 1 pass at a cutting speed of 2.5 m/min with gas pressure of 16 bar through a 1 mm gas nozzle. (a) side view, (b) top view

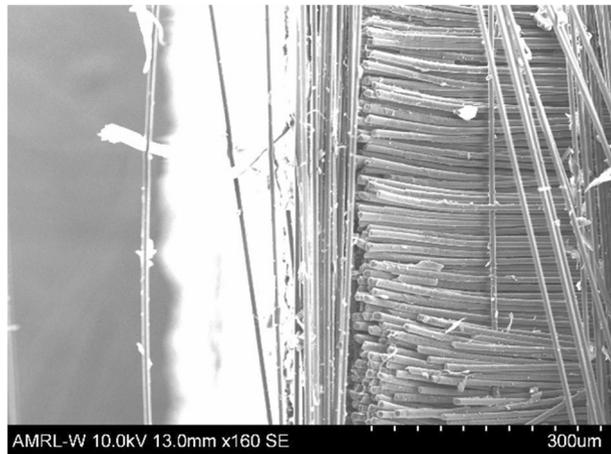
at 16 bar. Using these conditions, it was possible to split the CFRP material completely. It was also observed that as the cutting speed increased, the fiber damage decreased but the epoxy removal and top delamination increased.

Significant fraying was observed in experiments from the bottom and top of the material as shown in Fig. 5. This behavior is attributed to the loose weaving of the samples with large distance between weave knots. The fraying fibers belong to the top and bottom layers and can be observed in the microscopic images of the edge as depicted in Fig. 6. The results were also confirmed using SEM micrograph shown in Fig. 7.

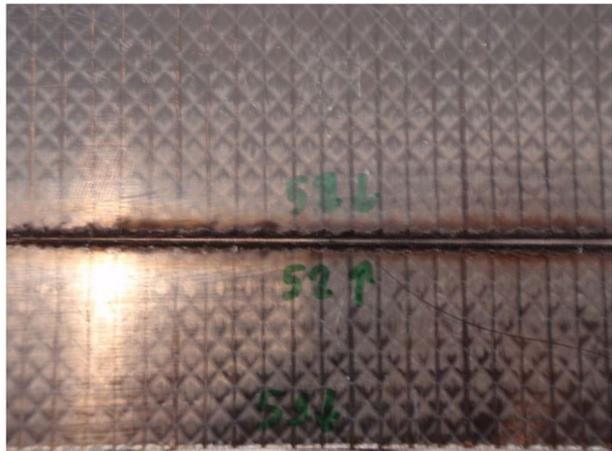
### Effect of multi-pass

The effect of multi-pass was investigated by increasing the number of passes to 2 and 3. With every incremental step the pass speed was also increased proportionally in order to maintain total cutting speed of 2.5 m/min, that is 2 and 3 passes were conducted with scanning speeds of 5 m/min and 7.5 m/min, respectively. It was noticed with increasing number of passes the fiber damage and top delamination had reduced. Furthermore, the linear speed was further increased to 10 m/min, and it resulted in reduction of fiber damage

**Fig. 7** SEM micrograph shown significant fraying



**Fig. 8** Photograph of test cut with no fraying

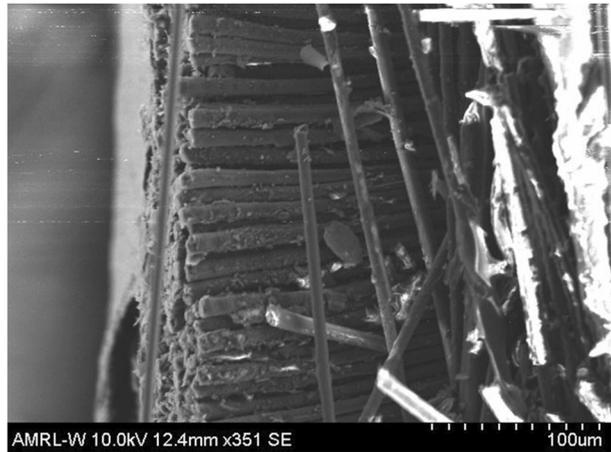


extent, top delamination, and epoxy removal. Whereas the bottom delamination increased by  $60\ \mu\text{m}$ , which was insignificant in previous cuts. The damage is possibly induced during the 3<sup>rd</sup> pass where pressurized gas and superheating by laser radiation forces the lower layer of fibers out of position. When the scanning speed was kept at  $10\ \text{m}/\text{min}$  and number of passes set to 2, the quality of measured characteristics decreases apart from the epoxy removal extent which reaches  $180\ \mu\text{m}$ . The averaged values of measured characteristics are shown in Table 5. Figure 8 shows the sample cut at cutting speed of  $2.5\ \text{m}/\text{min}$  with 3 passes and no fraying. Figure 9 shows the SEM micrograph with fiber damage extent at  $65.6\ \mu\text{m}$ .

### Investigation of stand-off distance

The optimization of stand-off distance did not show any noticeable improvements in the measured characteristics. But some visual improvement has been observed in terms of fiber orientation and delamination. The SEM micrographs of cuts at cutting speed of  $2.5\ \text{m}/\text{min}$  has shown a fiber damage extent of  $42.3\ \mu\text{m}$ .

**Fig. 9** SEM micrograph with fiber damage extent at 65.6  $\mu\text{m}$



### Investigation of large nozzle aperture

The nozzle aperture size was increased from 1.0 to 2.0 mm. However, this did not result in any meaningful enhancements of measured characteristics. The fiber damage extent and bottom delamination increased by factor of 1.5 and 2 when nozzle aperture size increased from 1.0 mm to 2.0 mm. Table 3 shows the measured characteristics of nozzle aperture at 2.0 mm. Figure 10 shows the photograph of test sample using 2 mm nozzle and 3 passes with significantly less fraying.

### Investigation of double aperture nozzle

Table 5 shows the measured characteristics using the double aperture. Fiber damage extent between 30–80  $\mu\text{m}$  was obtained using double aperture. Notably the epoxy removal extent was reduced to an average of 157  $\mu\text{m}$ . This is comparatively less than the average of

**Fig. 10** Test sample using 2 mm diameter nozzle and 3 passes



341  $\mu\text{m}$  for cuts using a 2.0 mm aperture and 345  $\mu\text{m}$  using 1.0 mm aperture. The double aperture nozzle works by generating a flow of high-pressure air directed downwards on the surface and less air is directed radially. This reduces the pressure that forces the top epoxy layer away from the laser radiation or gas flow during processing.

### Investigation of trenching

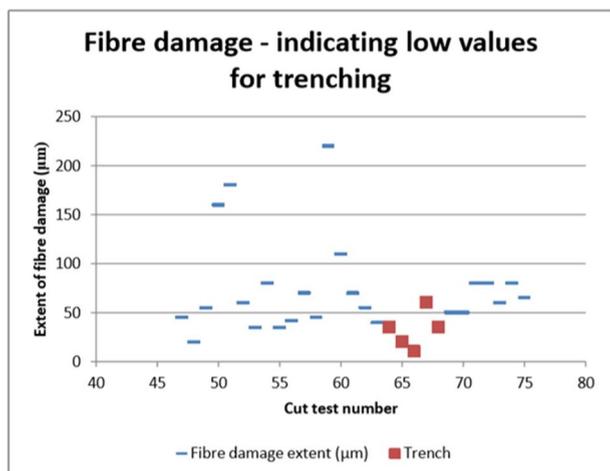
The results of the cutting characteristics for trenching are shown in Table 5. Two trench gap settings of 50  $\mu\text{m}$  and 100  $\mu\text{m}$  were used for trials at high scanning speed of 15 m/min. However, this failed to separate the sample having 2 mm thickness. Full cuts were achieved at comparatively less scanning speed of 7.5 m/min. Best results were achieved with a 1.0 mm nozzle and 100  $\mu\text{m}$  trench gap. A trench gap of 50  $\mu\text{m}$  achieved better results in terms of epoxy removal extent of 55  $\mu\text{m}$ . Most of the results were comparatively good with negligible fraying. An exceptional overall performance of trenching compared with single pass and multi-pass approaches is shown in Fig. 11. Using the trench method, it was concluded that an average fiber damage extent of 31  $\mu\text{m}$  and epoxy removal extent of 196  $\mu\text{m}$  was obtained when compared with other methods as shown in Table 5.

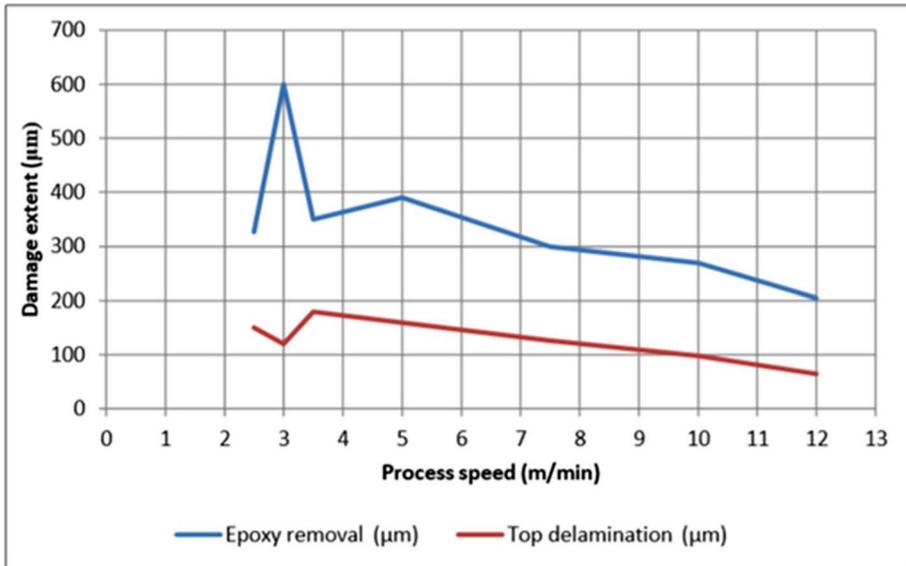
## Discussion

### Optimization and thermal guidelines

The epoxy removal extent was improved using a double aperture, achieving an average magnitude of 157  $\mu\text{m}$  from overall average of 308  $\mu\text{m}$  without using double aperture. The lowest epoxy removal extent attained was 110  $\mu\text{m}$  with trenching and 130  $\mu\text{m}$  without trenching. The average of epoxy removal and top delamination per test speed is shown in Fig. 12. It was observed that increasing the processing speed by adding more passes can improve epoxy removal extent and top delamination. This is due to the low beam dwell time, which is the dwell of the beam over the area that needs to be irradiated, taking place during the process,

**Fig. 11** Extent of fiber damage per cutting test and emphasizing the test results obtained with the use of trenching





**Fig. 12** Plot of measurement averages of epoxy removal and top- delamination for test speeds used in the current experiments

that allows the material to dissipate heat before it causes any damage until the next pass. Therefore, the multi-pass technique delivers the same amount of energy per irradiated area over longer time scale, which reduces the temporal energy density during each pass. This process has a greater impact on the top surface of the material as it is exposed to higher levels of direct optical energy resulting in greater localized thermal energy build-up.

Regularly better cut quality and good characteristics have been achieved using trenching when compared with other process parameters. Performance improvement comparison with measured values is shown on the chart in Fig. 13. On the chart cuts 67 to 71 were performed using trenching. In trenching beam intensity was maintained whereas, the overall energy per unit area delivered throughout this multi-pass process is reduced. This is useful as it causes sudden shattering of the material. Therefore, trenching can benefit the process results.

Thermographic analysis was carried out to characterize the trenching technique using a remote thermal camera that provides information of the highest recordable temperatures. A maximum temperature reading of 71.2 °C was recorded during the first trench pass, for the second and third trench passes the temperature recorded was 44.2 °C and 97.6 °C (Fig. 14), respectively. These temperature recordings show the maximum temperature that the material reaches during the cutting process. Also, the material does not undergo any significant thermal loading that may distort its shape as the maximum temperature raised recorded was below 100 °C in all tests, which is few a hundred degrees of Celsius below the melting temperature of the CFRP material.

### Shattering of fiber bundles

In materials such as steel and polymer, laser cutting can leave behind striations along the cutting length, with predominantly parallel orientation to the beam emission direction.

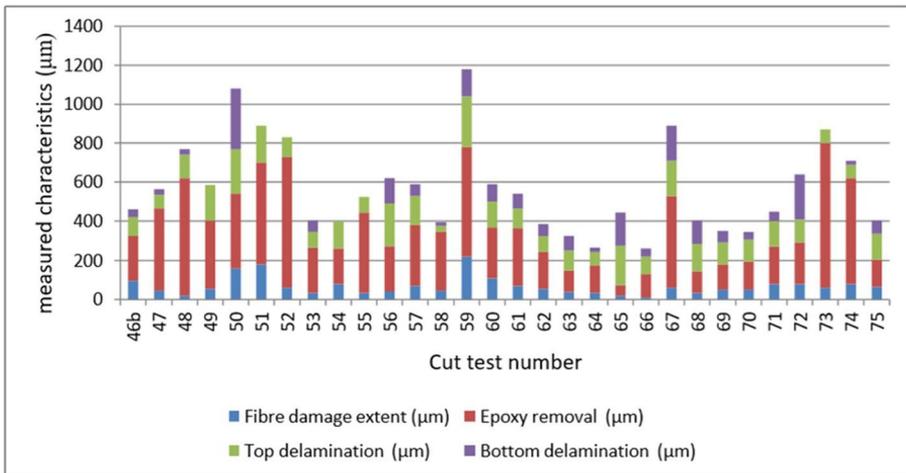


Fig. 13 Chart depicting the measured cut quality characteristics of each cut

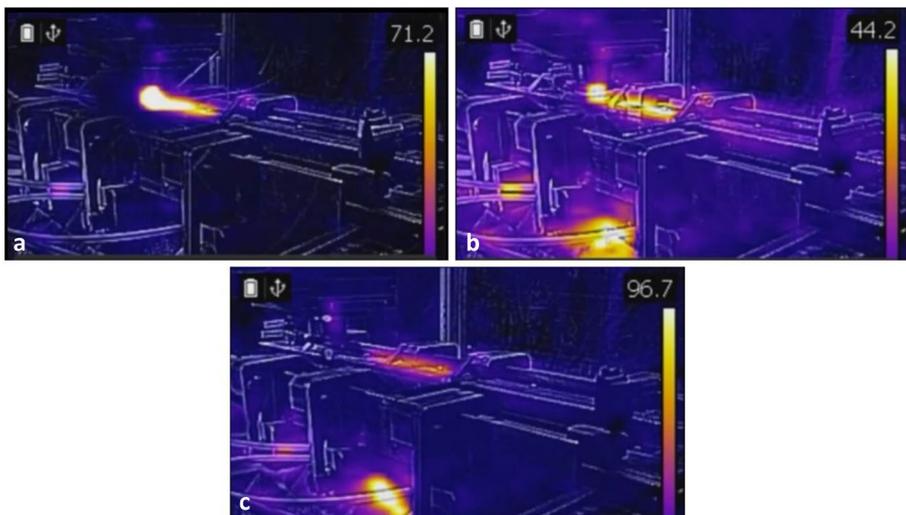
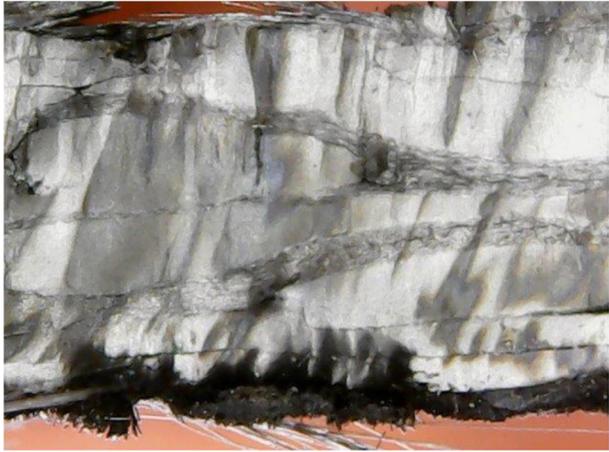


Fig. 14 Thermal images of trenching (a) First pass, (b) Second pass, (c) Third pass

This has only been observed in samples which are subjected to a double pass at higher speeds (Fig. 15). Thus, the striations in this case are presumed to have occurred from a possible small misalignment of the two beam passes. It is highly unlikely that the beam can bend, deflect, and cut individual weaving layers at different vertical positions with a distance between them of several hundred microns. Instead, the phenomenon resembles the behavior of a glass, when shattering or being subjected to a technique like thermal laser cleaving or other similar methods. The behavior is thus explained as a layer-by-layer shattering effect. The layers corresponding to the weaving bundles, behaving as materials of a

**Fig. 15** Surface striations for multi-pass cut

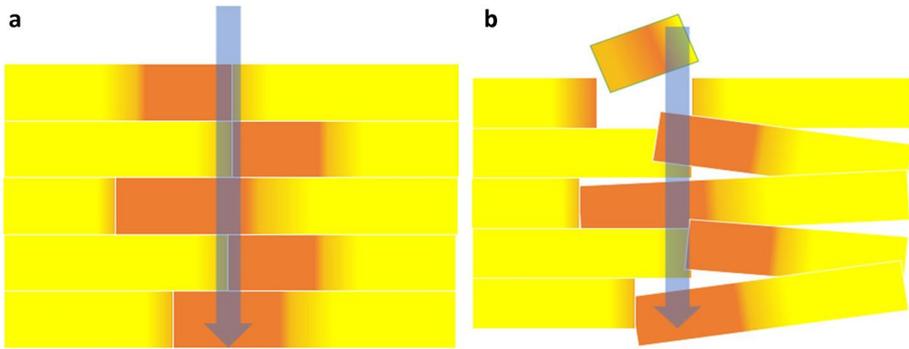


glassy or crystalline nature. As the carbon fibers are expected to demonstrate large tensile and yield strength, but very little plastic deformation, it is likely that the weaving bundles behave as extremely rigid strands of material that instead of melting or plastically deforming when subject to high temperature, they shatter at the weakest point of the bundle. These weak points can be distributed randomly along the bundle. Additionally, considering that temperature conduction is also affected significantly by the weaving direction and contact of the fibers in the bundle, the thermal gradients are not homogenous across the bundles in the material and thus the points prone to shattering are expected to be quite scattered at the microscopic scale. Considering the above, two scenarios are proposed to explain the shattering behavior of the material under intense laser irradiation with a small beam, in conjunction with large surface level variations.

The first scenario assumes that the material is semi-transparent to the beam's wavelength. Presently, this was not the case as the material appears black to the visible spectrum, thus fully absorbent. The binder may or may not be black colored as most polymers and epoxy binders are typically transparent in visible and much more transparent in NIR wavelength of laser emission. If optically absorbent, the assumption is that it vaporizes instantly around the beam or is displaced between the fibers, thus allowing the beam to propagate through the fibers. Fibers were assumed to originate from poly-acrylonitrile (PAN). However, it is not certain whether they have been just oxidized, stress graphitized or carbonized at high temperature and inert atmosphere.

This plays significant role in the optical absorption characteristics of the fibers. A full carbonization at high temperature generates true graphite rings, whose pi-bonds absorb a very wide spectrum of light typically encompassing the 1  $\mu\text{m}$  emission of this laser. The other two methods do generate ring-based polymer fibers; however, the electronic absorption band of those rings is limited due to the inclusion of nitrogen and oxygen atoms in the circular monomers. NIR radiation may well be transmitting or partially transmitting through these molecules.

Therefore, in the first scenario, the beam heats up the layers by transmitting through them, either due to inherent transmittance or induced transmittance via reverse photonic transformation. Heat conduction and thermal gradients across the weave bundles is different for each one, thus, the breakage can follow a jiggered line through the thickness of the material as shown in Fig. 16(a), defined by the points of higher temperature gradient as well as local material weakness in each bundle.



**Fig. 16** (a) First scenario, a crack propagating through the points of greatest thermal gradient in each bundle, (b) Second scenario, blocks of material from each bundle, snapping off, either side of the axis of highest temperature

The second scenario still considers that bundle breakage occurs at points of highest temperature gradients and thus temperature induced stress as shown in Fig. 16(b). Nonetheless, these happen around the beam and thus forcing pieces to be ejected from the material's body during irradiation. They are then propelled away from the kerf, most likely from the evaporation of the binder matrix. In this scenario, the beam shatters and removes block by block of the material in the area being irradiated and thus manages to penetrate all the way down to the bottom of the material. The scenario is applicable with the fibers being absorbent at  $1\ \mu\text{m}$  or having any degree of transparency. The blocks removed are uneven in size through the depth of the cut due to variations in the weaving direction and other material inhomogeneities.

Both scenarios can explain the surface level variation on the kerf edge and accept the glassy behavior of the bundles under thermomechanical stress and large temperature gradients. Consequently, a higher average power by a few kW and corresponding beam intensity at the target, will not result in a much smoother kerf edge, unless if transgressing to several tens of  $\text{GW}/\text{cm}^2$  of beam intensity.

Higher power can be used to increase processing speed proportionally, with the same finish being achieved. Better control of the surface finish at the kerf can only be obtained via a much higher photon energy, e.g., by green, blue or UV photons or by processing with ultrashort laser pulses and thus peak intensities of several  $\text{GW}/\text{cm}^2$  towards  $\text{TW}/\text{cm}^2$ .

## Conclusion

In the experimental study, the effects of different laser cutting process parameters on the surface quality of the CFRP were analysed. It was concluded that the behaviour of the material during cutting is attributed to the wide weaving, specifically on the top and bottom layers, where the material suffers significant amounts of fraying when processed. It is possible to compensate multiple passes with processing each pass at an equivalent higher speed. In fact, an overall speed advantage can be gained when taking such an approach and making larger than proportionate speed increments. Multi-pass with 3 passes is found to be significantly suppressing top and bottom fraying and improving the cut quality, whether processed with large, small, or double aperture nozzles. Cuts performed using

single pass exceeds the target performance in terms of cutting speed and fibre damage. Trials performed using single pass achieved fibre damage below 100  $\mu\text{m}$ . Further single pass trials were conducted with different laser stand-off distances and fibre damage below 70  $\mu\text{m}$  were achieved at cutting speed achieved were between 2.5 m/min to 3.5 m/min.. Trenching returns more consistent quality of cuts. Trenching or double aperture processing achieves low extent of fibre damage, below 100  $\mu\text{m}$  and averaging around 50  $\mu\text{m}$ . It was also observed that sample temperature does not exceed 100 °C. Both trenching and double aperture technique opens the path to explore fiber laser cutting as a replacement to mechanical cutting for remanufacturing processes for better accuracy, productivity, and costs.

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**Data availability** Data sharing not applicable to this article as no data sets were generated or analysed during the current study.

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