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ORIGINAL ARTICLE

Laser beam machining of carbon fiber reinforced composites: a review

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Abstract

Carbon fiber reinforced polymer (CFRP) composites gained wide acceptance in aerospace, automotive and marine industries due to their superior properties. It became the major structural material that substitutes metals in many weight-critical components such as the new A350 and the B787 aircrafts, with composite content to exceed the 50%. Although CFRP structures are manufactured to near-net-shape, edge trimming, drilling, sawing, milling, and grinding operations are unavoidable. Being anisotropic, inhomogeneous and highly abrasive, their conventional machining is normally associated with delamination, fibers pull-out, inadequate surface quality, and tool wear. Other nontraditional processes which include abrasive water jet machining (AWJM), ultrasonic machining (USM), and electrodischarge machining (EDM) offer substitute to the conventional methods. Laser beam machining (LBM) is an emerging technology offering an excellent alternative for machining CFRP composites. This paper reviews the research work carried out in the area of LBM of CFRP materials. It reports the experimental and theoretical studies covering the process accuracy in terms kerf width, kerf depth and edge quality, and the thermal characteristics in terms of heat-affected zone (HAZ). Minimizing the kerf taper, increasing kerf depth, and eliminating the HAZ in the polymer matrix are considered the major obstacles of CFRP industrial applications. Methods of improving the machining productivity by reducing the machining time and increasing the material removal rate (MRR) and kerf depth are reviewed. Several mathematical and statistical modeling and optimization techniques have been critically examined. The concept of specific energy and its impact on HAZ and kerf width is introduced. The relationship between laser type and HAZ is discussed. The current work furthermore outlines the possible trends for future research.

Keywords CFRP · Composite · Heat-affected zone · Cutting · Drilling · Matrix · Kerf width

1 Introduction

Due to their high strength-to-weight ratios, corrosion resistance, and low thermal expansion, CFRP composites have become attractive for use in many applications including aerospace, automobile, marine, medical, and sports components [1–3]. In the aerospace industry, CFRP is used in aeroengine fan blades, fuselage, and wing construction. Conventional machining of CFRP composites leads to excessive tool wear and delamination [4–10]. The frequent replacement of tools adds extra production time and cost. CFRP composites can also be machined by abrasive water jet (AWJM), ultrasonic machining (USM), LBM, and electrodischarge machining (EDM). These processes have different economical desirability levels as shown in Fig. 1 [12]. For lower tool wear and no HAZ, AWJM was recommended despite the noise hazards, abrasive slurry disposal, material delamination, and the moisture introduction to the cut surfaces [2, 4, 13]. On the other hand, the low machining rate, tool wear, and the frequent replacement of tools/electrodes limit the utilization of EDM [14, 15] and USM for machining CFRP composites [16].

The use of laser as an alternative method for machining CFRP composites imparts several advantages including narrow kerf widths, higher cutting speeds, ease of automation, and absence of cutting forces and abrasives or liquid media.

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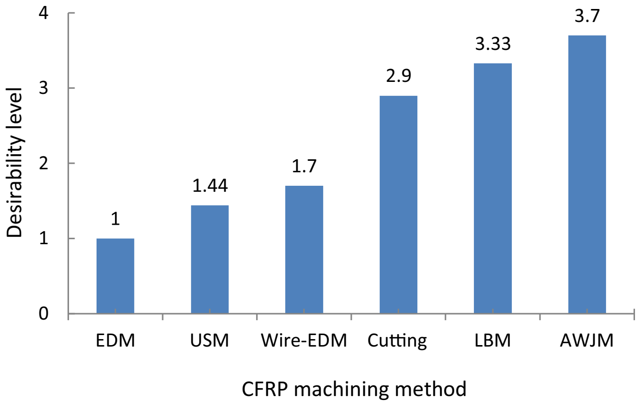

Fig. 1 Economic desirability of CFRP machining methods (Data from R Negarestani [11]

However, LBM possesses a major challenge due to the large differences in material properties of the two CFRP constituents at elevated temperatures [17–21]. Vaporization of fiber occurs at 3300 °C while that for the matrix occurs at 350–500 °C. Furthermore, the difference in thermal conductivities for graphite (50 W/m/°K) and for the polymer matrix (0.2 W/m/°K) makes it more difficult to achieve uniform, high-quality laser cuts since the heat conduction along the carbon fiber is much faster than that in the polymer matrix. Moreover, the heat conduction parallel to the fiber axis is faster than it is in the transverse direction, Fig. 2, which results in a non-uniform HAZ and acts as triggers for fatigue damage progression [23] or reduce the peak stress in laser-contoured CFRP parts [24]. The anisotropic heat conduction at different fiber orientations is another problem that affects the extent of HAZ. Consequently, the polymer matrix is further heated up by the hot fiber resulting in an extended polymer removal or degradation around the fibers [22, 25]. Eliminating or reducing HAZ is, therefore, a major challenge in laser machining of CFRP. Different process parameters including laser wavelength, beam transverse mode, pulse duration, repetition rate, laser power, energy density, beam spot size, scanning speed, and machining strategy affect the surface quality and kerf taper produced in CFRP composite. Figure 3 shows the parameters affecting the quality of laser machined parts [26].

A large body of research has reported investigations regarding CFRP laser cutting, drilling, milling, and trimming processes, for an understanding of the basic phenomena underlying the material removal process. Different types of lasers such as CO_2, Nd:YAG, excimer, and fiber lasers were used to investigate the effect of different parameters on the process performance. Most of the published work dealt with reducing HAZ, improving the product accuracy (kerf width and taper), enhancing LBM capability (material removal rate, kerf depth, and machining speed), and modeling and optimization of the process performance [27].

As shown in Fig. 4, the current review involves several aspects such as the machining accuracy (kerf width and kerf taper) and the HAZ, covered in Section 2, enhancing process performance by increasing the kerf depth and cut thickness or increasing the machining speed, efficiency, and productivity in Section 3. Modeling and optimization techniques using statistical methods or numerical techniques are covered in Section 4. Discussion of results regarding the effect of laser type on HAZ and impact of the specific energy on HAZ and kerf width are presented in Section 5. Summary and outlook are covered in Sections 6 and 7 respectively.

2 Accuracy and heat-affected zone

Laser machining of CFRPs is based on the interaction of the laser beam with two different materials having different thermal properties thus leading to HAZ, charring, matrix recession, and delamination which affect the quality of CFRP laser cutting. In this respect, because the time elapsed before the vaporization of the carbon fibers is larger than that of the resin; a large amount of heat is absorbed by the matrix which is associated by matrix burning and delamination of fibers [17]. The HAZ is strictly dependent on the adopted laser source and the working parameters [10]. C Leone et al. [28] developed a new parameter that describes the HAZ extension as a function of process conditions which takes into account

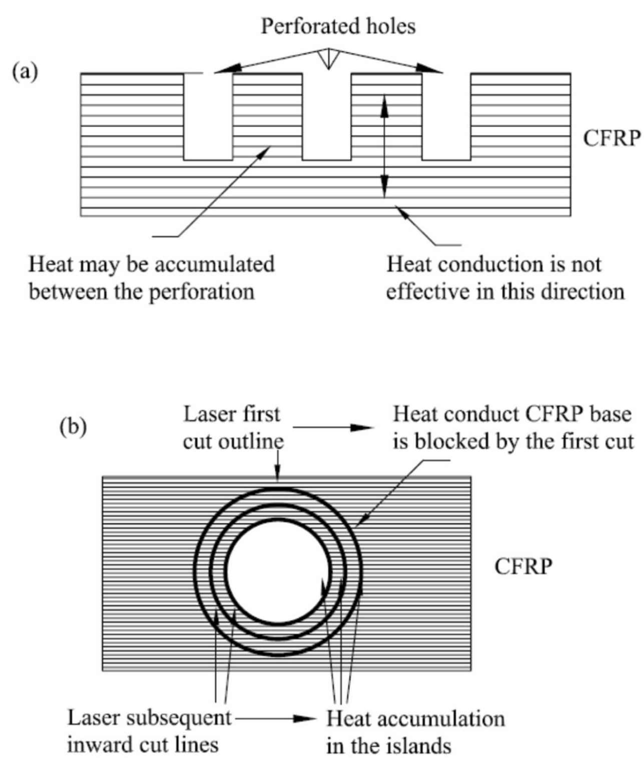

Fig. 2 Heat accumulations in CFRP laser machining **a** cross sectional view of perforation—thermal damage between holes caused by heat accumulation, **b** top view of laser scan traces in drilling a hole—enhancement of cutting efficiency due to heat accumulation [22]

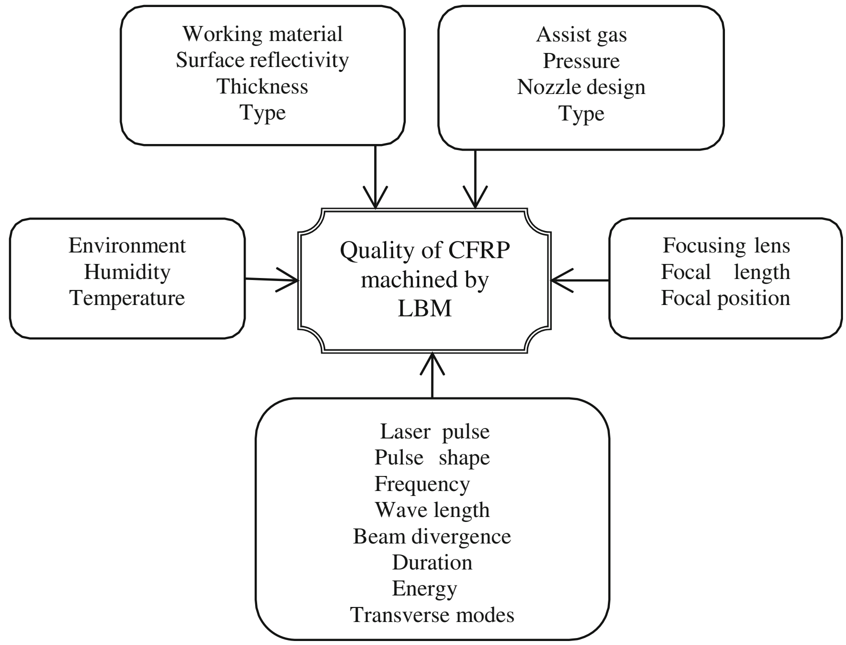

Fig. 3 Parameters affecting the quality of laser-machined parts [26]

the average power, the cutting speed, the pulse frequency, and pulse duration in a single parameter.

In order to reduce the laser–material interaction time and, hence, the HAZ, high scanning speed, increased spacing between adjacent laser beam scan traces, and low laser power were recommended by Z.L. Li et al. [22]. They used Nd:YVO_4 short pulsed laser having a wavelength 355 nm, pulse width 25 ns, average power 10 W, and pulse frequency 40 kHz to cut 7 mm-thick CFRP at a cutting speed 6 m/min. They reported a heat damage of 60 μm to the polymer matrix that was significantly increased at high laser powers. However, the use of high laser power enabled higher cutting speeds which produced smaller HAZ [29].The effect of pulse duration and spot overlap percentage was investigated by I. De Iorio et al. [4] and C Leone et al. [30] who used 100 W pulsed Nd:YAG for cutting 1 mm-thick CFRP laminates. Short pulses achieved the highest cutting speed of 11 mm/s and the HAZ of 1000 μm were achieved at a shorter pulse duration and spot overlap percentage. A narrow kerf width of 0.3 mm was also reported at small spot overlap or increased cutting speed. In this context, C Loumena et al. [6] used short and ultra-short pulses having a wavelength between 515 and 1030 nm for cutting millimeter to 0.75 mm-thick CFRP. Accordingly, HAZ was reduced when using ultra-short pulses [12]. Further reduction of HAZ (10–20 μm) was achieved at high machining speed of 70 mm/s using high power (60 W) hybrid fiber laser of 355 nm when cutting 250-μm-thick plates [31].

In order to improve the cut quality and reduce surface defects, Johannes Stock et al. [32] added light-absorbing soot particles to the resin of the matrix for cutting 2.2 mm CFRP using 3 kW fiber laser, 1068 nm wavelength. They reported a HAZ up to 1 mm that was significantly reduced by using a time delay of 150 ms between the ablation passes. A. Riveiro et al. [18] used CO_2 laser for cutting of 3 mm-thick CFRP composite in a continuous wave (CW) (300–200 W, 3.3–66.66 mm/s) and pulsed mode (PM) (300–3000 W, pulse frequency 10–4000 Hz and duty cycle 20-100). Accordingly, the

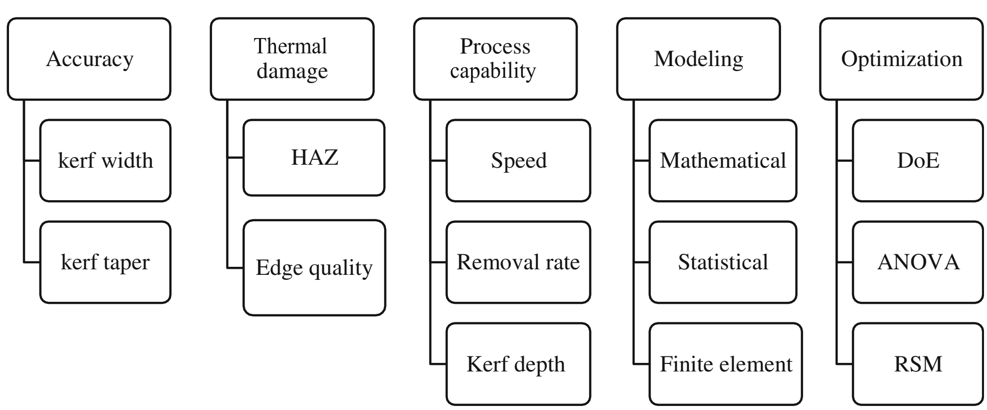

Fig. 4 Review directions of CFRP laser machining

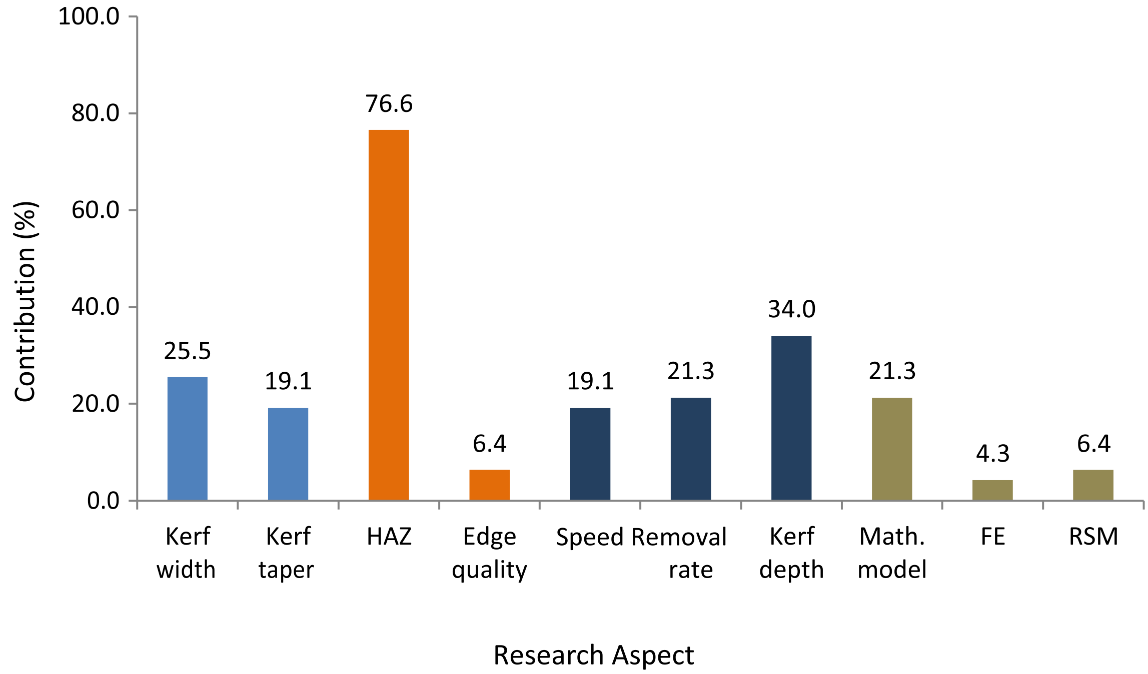

Fig. 5 Percentage contributions of researchers in different aspects of CFRP laser machining

CW was associated by the high thermal release that destroyed the polymeric matrix while cuts with a minimum HAZ of 540 μm were achieved using the CO_2 PM. Additionally, kerf width was in the range of 0.15–0.2 mm while the taper angle was between 0.01° and 0.02°.

The wavelength of laser radiation and, therefore, the absorption into the material have a significant effect on HAZ and the maximum CFRP laminate thickness that can be cut. In this regard, Sato et al. [33] compared UV and IR nanosecond lasers of two different wavelengths to cut 0.6 mm multi-directional CFRP stack using laser power, pulse width and frequency, spot size and the scanning speed of 4.7 × 109 W/cm^2, 6 ns, 10 Hz, 100 μm, and 1 mm/s, respectively. The cutting rate of IR laser having a wavelength 1064 nm was 0.85 μm/pulse while that for the UV laser having a wavelength of 266 nm was 0.60 μm/pulse. However, the HAZ of the 1064 nm IR laser was 105 μm, while that for the 266 nm UV laser was 88 μm. Therefore, the use of IR laser increased the material removal rate (MRR) and reduced the HAZ [31].

The extent of HAZ depends on the workpiece thickness [29], the type of matrix material [34], and the thermal properties of the fibers used. Islam Shyha [34] used a 500 W CO_2 laser for cutting 3 mm unidirectional (UD) GFRP and CFRP laminate. Maximum MRR of 8 cm^3/min was achieved when trimming GFRP at 29.17 mm/s cutting speed, 2500 W, and 5 bar gas respectively. An average surface roughness between 2.7 and 6.3 μm Ra and a kerf width of 0.28 mm were reported. These findings agree with the work of Patrick Hirsch et al. [35] who presented the effect of thermal properties of fiber-reinforced polyamide 6 (PA6) matrix and fiber content 60 wt% of continuous glass fiber PA6/GF60 and continuous carbon fiber PA6/CF60 composites. They concluded that at the same scanning speed, the single mode fiber laser cutting produces larger HAZ in PA6/GF60 as compared to the carbon fiber reinforced composites PA6/CF60.

The length of fibers affects the both the HAZ and kerf width. Jung Kwang-Woom et al. [36] achieved a narrow HAZ of less than 50 μm and kerf width of 200 μm using a laser power of 2–5 kW, cutting speed of 5 m/s, a time interval between repeated runs of 1 s, and defocused distance of 0 mm. Shorter fiber pellets were more easily cut and suffered less thermal damage than longer fibers. Both HAZ and kerf widths were reduced by increasing the cutting speed. In the same context, R Negarestani and Lin Le [12] used high power single-Ytterbium-doped fiber laser (1 kW) to cut a 2 mm CFRP at 4.8 m/min in the presence of N_2 gas. They reported that the use of short and ultra-short pulses, high cutting speeds, and multiple pass cutting strategy, low beam intensity, and additional N_2 gas reduced the thermal damage. HAZ was 350 μm while the kerf width was 250 μm. The cut quality was also improved using high pressure assist gas while the use of oxygen increased the thermal damage through oxidation. Focusing of the beam below the material was found effective in reducing the extent of thermal damage. Additionally, the multiple-pass cutting technique minimized the delamination at low power levels and high scanning speeds. The CW fiber laser showed a notable reduction of delamination as the scanning speed was increased.

Minimizing the kerf width using the DoE technique was investigated by M.S. Wahab et al. [37] who used Nd:YAG

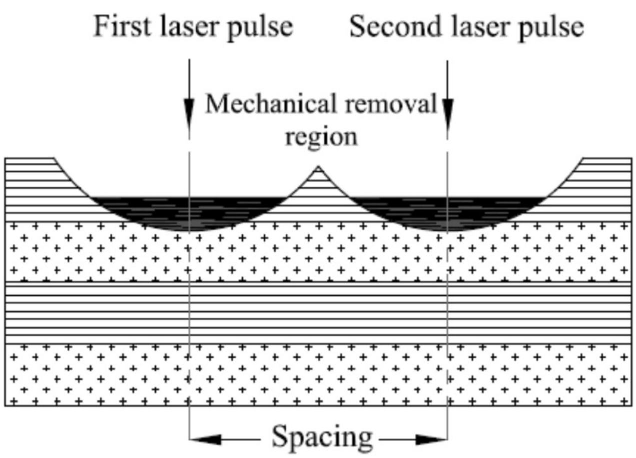

Fig. 6 Ablation schematic of two adjacent pulses [2]

laser (1064 nm, 300 W, pulse duration 0.5–0.8 ms, repetition rate 35–45 Hz) to cut 3.0 mm CFRP. Accordingly, pulse repetition rate and pulse duration were the most significant factors for minimizing the top kerf width. The optimum parameters were found to be at1.4 J pulse energy, 40 Hz repetition rate, 0.8 ms pulse duration, and 0.048 m/min cutting speed. Similar observations were reported by the same authors in reference [10].

In order to reduce the interaction time between the laser beam and the CFRP material, the layer-by-layer strategy was experimented during laser milling of 2 mm thickness by Jun Hu and Hebing Xu [2] using, Nd:YVO_4, 532 nm ns pulsed laser 20 W, 50 kHz, 1 and 2 ns pulse length. Large HAZ was associated with high power and low scanning speed while furrow-like surface morphology was evident when the hatch distance was greater than the beam spot diameter. They recommended adjusting the focus plane on the machined surface after several scanning passes in order to avoid the defocus environment which decreased the MRR and the machining efficiency. Similarly, a multi-pass strategy was adopted by Dirk Herzog et al. [38] who used the laser beam to cut 6 mm CFRP at a high delay of 2 s between passes to avoid heat accumulation which occurs with a high number of passes. The effectiveness of using multiple pass technique together

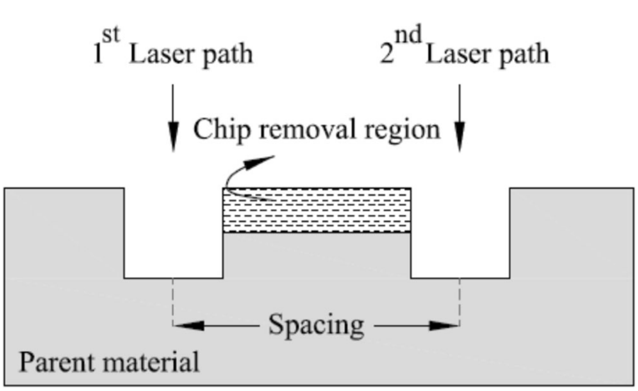

Fig. 7 Laser beam scanning on two tracks with double-line cutting [11]

with the ultra-high power pulses in reducing HAZ and energy input and increasing the effective feed rate was investigated by Dirk Herzog et al. [5]. They used 30.5 kW Yt:YAG fiber laser to cut 1.4 mm CFRP plate in a single pass at a cutting speed of 1.2 m/s with mean HAZ of 139 μm that were reduced to 78 μm (56%) when using 12 passes. The energy input was also reduced by 26% and the effective feed rate was increased by 35% (1.63 m/s). They observed fissures and chipping close to the surface of specimens that were related to the insufficient absorption of the laser wavelength by the matrix, leading to fast energy deposition and partial evaporation below the machined surface. For effective material ejection from the machining zone, improving the machining quality and enhancing the machining rate. A Salama et al. [19] adopted the multiple ring material removal strategy to widen the cut at the beam entry side which reduced the shielding of the incident laser by the plume generated during CFRP laser machining. They drilled 6 mm diameter holes in 6 mm-thick CFRP using 400-W (PS) laser at a scanning speed of 2 m/s. HAZ was 25 μm at the entrance side and holes showed a taper angle 15° that was reduced by tilting of the workpiece or offsetting the laser beam. The flow speed of the material vapor cloud generated during laser drilling of CFRP with the continuous laser beam was found to propagate at speeds between 4500 and 5000 m/s [39]. Such a vapor forms hazardous substances which need to be considered when machining CFRP composites [40].

Furthermore, A. Riveiro et al. [41] reported that the coaxial subsonic and off-axial supersonic assist gas jets gave similar HAZ extension. The protruding fibers were clear when using off-axial supersonic jets. Reduced laser powers to 1600 W and increased cutting speed from 2 to 4 m/min avoided the excessive thermal input into the workpiece, and achieved sound cuts Shidayal Rao et al. [6]. Volkher Onuseit et al. [42] claimed that the damage-free laser processing of CFRP was possible when using high laser intensities above 108 W/cm^2 and avoiding any kind of heat accumulation in the machining zone. To reach such an intensity, it was recommended to use short and ultra-short pulsed lasers with a pulse duration of several nanosecond down to picosecond (PS) [19]. Recently, Dong Sun et al. [43] introduced the hybrid water jet-guided laser (WJGL) machining of CFRP and concluded that the new technique produces no HAZ compared to the conventional LBM due to the strong convection cooling effect of the water jet. However, the effective cutting speed is 50 times slower than LBM.

3 Enhancing process capability

LBM productivity is expressed in terms of machining speed/cutting time, material removal rate and kerf depth. These points were covered by many researchers where 19% of them

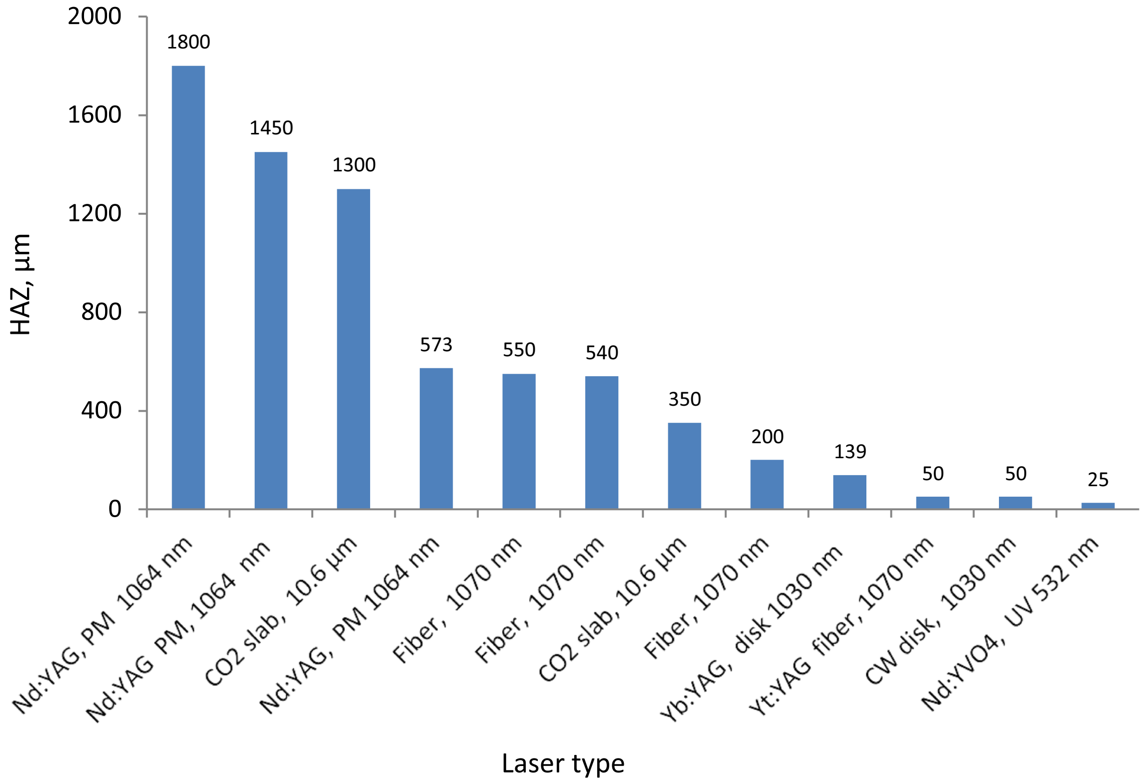

Fig. 8 Heat affected zone by different laser types

studied the machining speed, 21% dealt with removal rate, while 34% were attempting to increase the kerf depth, (Fig. 5). Cutting large CFRP thickness and kerf depth were investigated in references [7, 20, 38, 44–46]. In this regard, A Goeke and C. Emmelmann [20] machined CFRP laminates up to a thickness of 7.0 mm by the CO_2 laser (10.6 µm wavelength) and up to 5.0 mm by the fiber laser (1.07 mm wavelength) giving a rise in the machining productivity by 40%. Increasing the CFRP thickness to 9.2 mm CFRP plate using argon gas assistance (30 l/min) and high power fiber laser was introduced by H. Hira and A. Tsuboi [44]. Accordingly, cutting speeds of 10 m/min, with a corresponding energy input per unit length 0.5 W min/mm respectively were achieved. In a further work, Keisuke Ushida et al. [7] reported the increase of kerf depth at lower scanning speeds and larger percentage of overlapping areas. An optimum focus position for each speed that achieved a maximum cut depth was reported. For achieving larger kerf depth, S Bluemel et al. [45] suggested an optimum repetition rate from 5 to 50 kHz. The use of multi-pass strategy was adopted to increase the kerf depth by Dirk Herzog et al. [38] who used 6-kW power Yb:YAG disk laser for drilling deeper kerfs at a scanning speed 2 m/s and constant focus position on top of the material. Using the single pass method, the kerf depth increase was found constant (5 mm) after 17 passes, after which the process lost efficiency [46]. Kerf bending resulted from multiple reflections of the laser beam at the kerf walls was the main reason behind the achieving deeper kerfs. When the focus was retraced by 5 mm into the material after 17 passes, the kerf depth was not further increased due to the shadowing effect where the narrow cut width at the top of the material does not allow the whole beam waist to enter the cut. The parallel passes increased the kerf width at the top of the material and the focus was retraced, the shadowing effect was avoided and a maximum kerf depth of 12.7 mm after 168 passes was achieved. The extension of the HAZ showed almost no increase with the number of passes and was in the range of ≈ 200 µm even for the parallel passes approach.

Enhancing the machining speed, efficiency, and productivity was covered in many references [31, 47–49]. The use of high power and programmable pulse width/shape result in both high speed and quality of CFRP [31]. During helical drilling of 1 mm diameter hole in 4 mm-thick UD CFRP using 7 W, pulse repetition rate 20 kHz, pulse duration 20 ns, scanning speed 25 mm/s, and pulse overlap 91.7%, the process productivity was increased by a factor of 2. When the same strategy was adopted for milling linear slots at 15 W, 8 kHz, and 0.2 m/s speed, pulse overlap 25% the productivity was increased by a factor of 7 [47]. In a further work, S Bluemel and coworkers [48] studied the effect of fiber diameter on the quality and efficiency of the cutting process. Accordingly, by using 400-µm fiber, it was possible to cut faster in comparison to 600-µm fiber. Hiroyuki Niino et al. [49] performed micro cutting of 3 mm CFRTP-ABS and CFRP-PPS using CW near

Table 1 Specific energy, HAZ and kerf width by different laser types

Laser type	Wave length	Reference	Machining conditions			Energy index, J/mm^2	HAZ µm	Kerf width µm
			Thickness, mm	Power, W	Speed, mm/s			
Nd:YAG pulsed	1064 nm	J Mathew et al. [1]	2	300	0.8	187.5	1800	300
CO_2 TEA pulsed	10.6 µm	A. Salama et al. [3]	1.5	300	45	4.44	25	–
Yt:YAG fiber	1070 nm	D Herzog et al. [5]	1.4	30,500	1200	18.15	139	–
Fiber	1070 nm	S l Rao et al. [6]	1.4	400	75	3.81	573	163
Fiber	1070 nm	R Negarestani et al. [12]	2	1000	80	6.25	350	250
Nd:YAG pulsed	1064 nm	I. De Iorio et al. [17]	1	100	1.1	90.91	1300	300
CO_2 slab	10.6 µm	A. Riveiro et al. [18]	3	200	66.7	1	540	200
Fiber	1070 nm	A. Goeke et al. [20]	5	1500	83.3	3.6	550	200
Nd:YVO$_4$ ns UV	532 nm	Z. L. Li et al. [22]	7	10	100	0.01	50	–
CO_2, CW	10.6 µm	I Shyhaa [34]	3	2500	29.2	28.57	–	–
CW disk	1030 nm	J K Woon et al. [36]	3	5000	5000	0.33	50	200
Yb:YAG, disk l	1030 nm	D Herzog et al. [38]	12.7	6000	2000	0.24	200	–
CO_2 slab	10.6 µm	A. Riveiro et al. [41]	3	3500	66.7	17.5	1450	200

IR laser of an average power 2–3 kW. Their results showed that 15 passes were needed to cut through CFRTP-ABS while 27 passes were needed for CFRTP-PPS at 3.6 mm/s. This means that the cutting time is almost doubled (productivity decreased by 50%) in the latter case. Pulse power was the important factor for the complete cutting of 3 mm.

4 Modeling and optimization

Several attempts have been made to model the heat flow [11] and the material removal mechanism [50]. Other researchers adopted statistical methods [1, 3, 6, 37] or numerical techniques [11, 46, 50–55] and to optimize the process conditions towards minimizing HAZ and kerf width and taper, maximizing the energy utilization and enhancing the machining productivity and quality [31]. Modeling and optimization was done using the DoE [1, 3, 6, 37] such as Taguchi technique and response surface methodology (RSM). The significant effect of process control parameters and their interactions on HAZ and cut quality characteristics (kerf width, depth, and taper) were analyzed using the analysis of variance (ANOVA) technique. In this respect, M.S. Wahab et al. [37] used the DoE technique to provide the optimum laser cutting parameters for minimizing the kerf width at the top and bottom surfaces. On the other hand, Jose Mathew et al. [1] adopted the RSM methodology to developed predictive models for HAZ and kerf taper when using 300 W pulsed Nd:YAG laser to cut a 2 mm thickness CFRP. Accordingly, HAZ width of 1.8 mm was influenced by the pulse repetition rate, cutting speed, pulse duration, and beam energy while the kerf width (0.3 mm) was affected by the assisting gas pressure. The optimum cutting speed of 0.5–0.8 mm/s, pulse energy 1.5–2 J, pulse duration 0.4–0.7 ms, pulse repetition rate 35–45 Hz, and gas pressure of 5–7 kg/cm^2 were reported. A Salama et al. [3] used the DoE and statistical modeling, based on the RSM to understand the main and interaction effects between the laser fluence, repetition rate, and cutting speed on the cut quality characteristics including HAZ, kerf depth, and MRR. Thermal damage on the top surface was significantly reduced to 57–75 µm by using a suitable sacrificial metal mask. The optimum HAZ, kerf depth, and MRR were 21 ± 4 µm, 5.8 ± 0.3 µm/pass, and 11 ± 0.4 mm^3/min, respectively. Shivdayal Rao et al. [6] used the RSM to optimize the process parameters for better cut surface quality of 1.4 mm thick unidirectional CFRP using fiber laser of 1070 nm wavelength. Optimum process parameters with minimum surface defects were at laser power 260 W, cutting speed 75 mm/s, and assistance gas flow rate 14.23 *l*/min. The corresponding kerf width, taper percentage, and HAZ width were 163.7 µm, 5.75%, and 573.28 µm respectively.

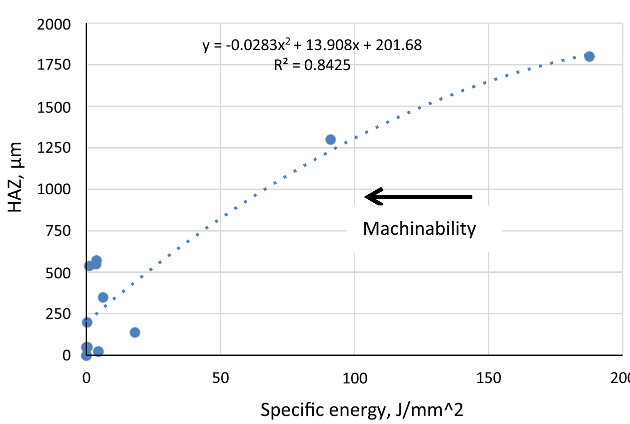

Fig. 9 Effect of the specific energy on HAZ and machinability

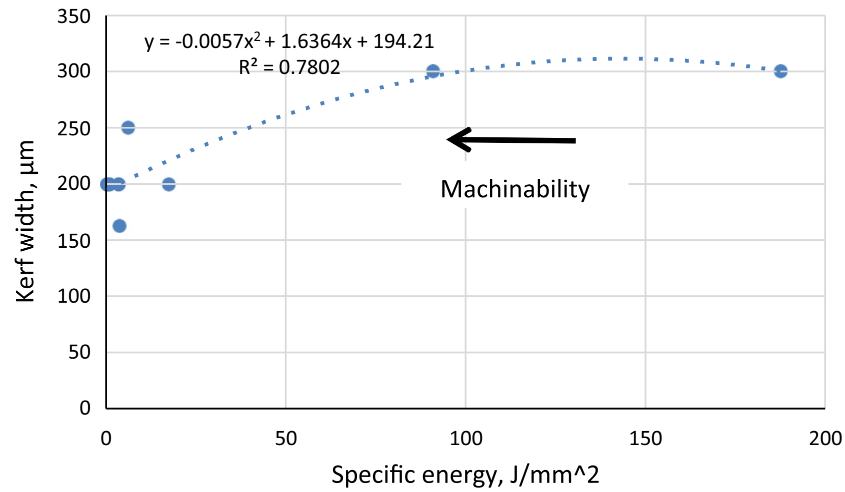

Fig. 10 Effect of the specific energy on kerf width and machinability

Mathematical and numerical methods have been used to understand the process characteristics [11, 46, 50–55]. A Salama et al. [51] proposed a mathematical model to determine the maximum kerf depth for single and multiple rings (parallel tracks). Their model was experimentally validated and the results showed that the maximum drilling depth and MRR were significantly improved by increasing the number of parallel passes under the same energy delivery and scanning speed. R Negarestani et al. [11] presented a 3D FE model to simulate the heat flow and MRR of pulsed laser cutting of 0.3 to 1 mm-thick CFRP using 355 nm DPSS Nd:YVO_4 UV laser of frequency 40 kHz, and power of 10 W. Accordingly, HAZ and ablation depth were more sensitive to the cutting speed in the lower range of 50–200 mm/s as compared to the high range of 200–800 mm/s. Burning was clear at low speed (50 mm/s) while fiber pull out, chip formation, and clean cuts were obvious at high speed of 800 mm/s as well as the double line processing. In the same line, Yan-Chi Liu et al. [52] developed a finite element (FE) model which predicted that about 10 s was enough to make a through hole in 2 mm-thick CFRP and was useful to predict the temperature and phase change during drilling CFRP using a pulsed laser. A numerical simulation of laser beam cutting was also introduced in reference [53] to model the mechanism of HAZ generation using the finite difference (FD) method. Their model was based on the assumption that heat source is not only laser power but also the decomposition or combustion heat at the boundary of the removed area and the resin of carbon fiber. Hebing Xu and Jun Hu [50] introduced a numerical model to describe the mechanism of the material removal during CFRP milling of 2 mm thick CFRP using ND:YVO_4 ns pulsed laser. They claimed that both laser ablation and mechanical erosion caused by the polymer pyrolysis were involved in the material removal process. An optimum spacing distance between two adjacent lasers pulses was recommended to utilize the mechanical erosion phase effectively, Fig. 7. Such spacing depends on the laser power, when it was too small; most of the material was removed by direct laser ablation which increased the heat input and consequently the HAZ. It is believed that similar hybrid thermal–mechanical removal mechanism occurs when using the double line scanning for cutting CFRP (Fig. 8).

Optimization of the energy and time efficiency as well as the HAZ during remote laser cutting was conducted by M Oberlander et al. [54] by measuring the reflected laser radiation during cutting 2 mm-thick CFRP using 6-kW disk laser power, 1030 nm wavelength, 4000 mm/s, and a delay of 400 ms between the exposures to minimize HAZ. Their algorithm was capable to detect the complete part separation and, hence, the termination of the cutting process after exposure thus optimizing the energy, time efficiency and minimizing the HAZ. An analytical and numerical approach of evaporation laser drilling, towards the theoretical determination of the process parameters that maximize energy efficiency has been developed. The physical mechanisms responsible for most of the energy losses were analyzed and classified according to their importance [46]. A perpendicular heat flow model was introduced by Rudolf Weber et al. [55] to calculate the minimum achievable damage in the matrix material. Their model was used to determine the optimum pulse parameters according to the quality needs.

5 Discussion

Table 1 summarizes the published CFRP laser cutting data regarding laser type and power, machining speed, and part thickness together with HAZ and kerf width. Accordingly, Fig. 8 shows the HAZ for different laser types. It is clear that HAZ is larger for the longer wavelength which can be explained by the wavelength effect on the absorption coefficient of epoxy resin [56, 57]. Table 1 also presents the calculated specific energy per unit cut area in J/mm^2. When using the laser power W to cut a thickness t (mm) at a cutting speed S (mm/s), the specific energy (J/mm^2) is given by:

$$\text{Specific energy}\left(\frac{\mathrm{J}}{\mathrm{mm}^2}\right) = \frac{\text{Cutting power (W)}}{\text{Cutting speed},\ \ S\left(\frac{\mathrm{mm}}{\mathrm{s}}\right)\mathrm{x}\ \ \text{Thickness},\ \ t\ (\mathrm{mm})}$$

Figure 9 shows that as the specific energy increases, the width of HAZ increases. Such a condition occurs when using high laser power (W) to cut small CFRP thickness (t) at small cutting speed (S). The use of high cutting power provides excess energy while low cutting speeds raise the beam interaction time with the CFRP material which in turn cause deeper HAZ. For the same power and cutting speed S, cutting smaller work thickness t restricts the heat flow in the CFRP materials, out of the cutting zone, thus causing wider HAZ. Similarly, Fig. 10 shows that the kerf width increases with increasing the specific energy. For a given cutting speed (S) and thickness (t), the increase of laser power (W) allows more energy to widen the kerf width. The use of low cutting speed (S) also provides more interaction time to widen the kerf. Additionally, as the thickness t becomes smaller the excessive energy density increases the kerf width. The specific energy can be used to express the machinability of CFRP composites. For high material machinability, the specific energy should be low. This means that less power (W) is utilized to cut large CFRP thickness t at high cutting speed S thus lowering both HAZ and kerf width. Smaller kerf width and HAZ are recommended for better accuracy and product quality.

6 Summary

In summary, laser machining of CFRP composites is an alternative method that replaces traditional and some nontraditional cutting processes. Form the literature review, the following conclusions can be raised:

1. In order to reduce HAZ, the use of short and ultra-short pulses, high cutting speeds, multipass cutting, low beam intensity, increased spacing between adjacent laser beam scan traces, and high pressure assist gas are recommended.
2. Both HAZ and kerf width decrease and the machinability improve by decreasing the specific energy that occurs when using larger laser power to cut large CFRP thickness at high cutting speed.
3. Laser ablation and mechanical erosion caused by the polymer pyrolysis contribute in the CFRP material removal mechanism.
4. The multipass processing strategy with well-adjusted scan speed and interval times between the scans achieved high-quality cut edges with acceptable productivity.
5. Machining CFRP composites using CW laser produced cuts with several defects while using the PM had the limitation of achieving deeper cuts due to the limited energy supplied

7 Outlook

There are critical problems encountered by many researchers during laser machining of CFRP composites. Further efforts are, therefore, to be made in the following directions:

1. Control of the thermal energy conducted into the matrix which causes HAZ, matrix recession, matrix decomposition and/or fiber delamination.
2. Optimization of the process parameters using the artificial neural network (ANN), fuzzy logic (FL), genetic algorithm (GA), gray relational analysis (GRA), artificial bee colony (ABC) multi-objective optimization, and simulated annealing (SA).
3. Modeling, simulation, and experimental investigation of machining laminates including laser absorbing and nano-sized particles in the matrix.
4. Increasing the cutting thickness of CFRP using the multipass strategy.
5. Investigating the contribution of laser ablation phase and mechanical erosion component caused by the polymer pyrolysis when using two adjacent laser pulses or two parallel lines.
6. Study the flow speed of the ablation vapors which limit the drilling depth and cutting large CFRP thickness.
7. Assessment of CFRP machinability indices at different machining parameters.
8. Evaluation of the hazards associated with CFRP laser machining.

Compliance with ethical standards

Conflict of interests The authors declare that there is no conflict of interests.

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References

1. Mathew J, Goswami GL, Ramakrishnan N, Naik NK (1999) Parametric studies on pulsed Nd:YAG laser cutting of carbon fibre reinforced plastic composites. J Mater Process Technol 89–90:198–203. https://doi.org/10.1016/S0924-0136(99)00011-4

2. Hu J, Xu H (2015) Pocket milling of carbon fiber-reinforced plastics using 532-nm nanosecond pulsed laser: an experimental investigation. J Compos Mater 50(20):2861–2869. https://doi.org/10.1177/0021998315614990
3. Salama A, Li L, Whitehead PM (2016b) TEA CO_2 laser machining of CFRP composite. Appl Phys A 122:497. https://doi.org/10.1007/s00339-016-0025-8
4. Loumena C, Nguyen M, Lopez J, Kling R (2018) Potentials for lasers in CFRP production. Journal of Laser Applications 1026. https://doi.org/10.2351/1.5062378
5. Herzog D, Schmidt-Lehr M, Canisius M, Oberlander M, Tasche J-P, Emmelmann C (2015) Laser cutting of carbon fibre reinforced plastics using a 30 kW fiber laser. J Laser Appl 27 Number: S28001–S28006. https://doi.org/10.2351/1.4906304
6. Rao S, Sethi A, Das AK, Mandal N, Kiran P, Ghosh R, Dixit AR, Mandal A. (2017) Fibre laser cutting of CFRP composites and optimization of process parameters through response surface methodology experiment preparation and condition. S Materials and Manufacturing Processes, Volume 32, Issue 14. https://doi.org/10.1080/10426914.2017.1279296
7. Ushida K, Inami W, Shimamura Y, Kawata Y (2012) Characteristic analysis of CFRP cutting with nanosecond pulsed laser. J Adv Res Phys 3(1):011211
8. Koenig W, Wulf C, Grass P, Willerchied H (1985) Machining of fiber reinforced plastics. Ann CIRP 34(2):537–548. https://doi.org/10.1016/S0007-8506(07)60186-3
9. Krishnaraj V, Prabukarthi A, Ramonathan A et al (2012) Optimization of machining parameters at high speed drilling of carbon fiber reinforces composites (CFRP) laminates. Compos Part B 43:1791–1799. https://doi.org/10.1016/j.compositesb.2012.01.007
10. Wahab MS, Rahim EA, Rahman NA, Uyub MF (2012) Laser cutting characteristic on the laminated carbon fiber reinforced plastic (CFRP) composite of aerospace structure panel. Adv Mater Res 576:503–506. https://doi.org/10.4028/www.scientific.net/AMR.576-503
11. Negarestani R, Sundar M, Sheikh MA, Mativenga P, Li L, Li ZL, Chu PL, Khin CC, Zheng HY, G C L (2010) Numerical simulation of laser machining of carbon-fibre- reinforced composites. Proc. IMechE Part B: J. Engineering Manufacture 224:1017–1027. https://doi.org/10.1243/09544054JEM1662
12. Negarestani R, Li L (2013) Fiber laser cutting of carbon fiber reinforced polymeric composites. Proc IMechE Part B, J Eng Manuf 227(12):1755–1766. https://doi.org/10.1177/0954405413490513
13. El-Hofy M, Helmy MO, Escobar-Palafox G, Kerrigan K, Scaife R, El-Hofy H (2018) Abrasive water jet machining of multidirectional CFRP laminates. Procedia CIRP 68:535–540. https://doi.org/10.1016/j.procir.2017.12.109
14. Habib S, Okada A (2016) Influence of electrical discharge machining parameters on cutting parameters of carbon fiber-reinforced plastic. Mach Sci Technol 20(1):99–114. https://doi.org/10.1080/10910344.2015.1133914
15. Habib SS (2014) Modeling of electrical discharge machining of CFRP using artificial neural network technique. JMMA 3(1):22–31
16. Helmy MO, El-Hofy MH, Hassan E-H (2018) Effect of cutting fluid delivery method on ultrasonic assisted edge trimming of multidirectional CFRP composites at different machining conditions. Procedia CIRP 68:450–455. https://doi.org/10.1016/j.procir.2017.12.077
17. De Iorio I, Leone C, Lopresto V, Pagano N (2010) Short pulse Nd:YAG laser cutting of CFRP sheet. World J Eng 7:289–290
18. Riveiro A, Quintero FL, Del Val J, Comesaña R, Boutinguiza M, Pou J (2012) Experimental study on the CO_2 laser cutting of carbon fibre reinforced plastic composite. Compos A: Appl Sci Manuf 43(8):1400–1409. https://doi.org/10.1016/j.compositesa.2012.02.012
19. Salama A, Li L, Mativenga P, Sabli A (2016) High power picosecond drilling/machining of carbon fibre-reinforces polymer (CFRP) composites. Appl Phys A 122(73):1–11
20. Goeke A, Emmelmann C (2010) Influence of laser cutting parameters on CFRP part quality. Phys Procedia 5:253–258. doi.org/10.1016/j.phpro.2010.08.051
21. Cenna A, Mathew P (1997) Evaluation of cut quality of fiber reinforced plastics- a review. Int Jr Machine Tools Manuf 37:723–736. https://doi.org/10.1016/S0890-6955(96)00085-5
22. Li ZL, Zheng HY, Lim GC, Chu PL, Li L (2010) Study on UV laser machining quality of carbon fiber reinforced composites. Composites: Part A 41:1403–1408. https://doi.org/10.1016/j.compositesa.2010.05.017
23. Kalyyanasundaram D, Gururaja S, Prajakta P, Singh D (2018) Open hole fatigue testing of laser machined MD-CFRPs. Compos Part A 111:33–31
24. Zaeh MF, Stock JW (2017) Peak stress reduction in the laser contouring of CFRP. CIRP Ann 66(1):249–252. https://doi.org/10.1016/j.compositesa.2018.05.005
25. Patel P, Gohil P, Rajpurohit S (2013) Laser machining of polymer matrix composites: scope, limitation and application. Int J Eng Trends Technol (IJETT) 4(6):2391–2399
26. El-Hofy H (2018) Fundamentals of machining processes: conventional and nonconventional processes, Third edn. CRC press, Taylor and Francis Ltd., Boca Raton
27. Dubey AK, Yadava V (2008) Laser beam machining- a review. Int J Mach Tools Manuf 48:609–628. https://doi.org/10.1016/j.ijmachtools.2007.10.017
28. Leone C, Genna S (2018) Heat affected zone in pulsed Nd:YAG laser cutting of CFRP. Compos Part B 140:174–182. https://doi.org/10.1016/j.compositesb.2017.12.028
29. Bluemel S, Jaeschke P, Wippo V, Bastick S, Stute U, Kracht D, Haferkamp H (2012) Laser machining of CFRP using high power fiber laser- investigations on the heat affected zone. 15th European conference on composite materials Venice Italy, 7 p
30. Leone C, Pagano N, Lopresto V, De Lorio I (2009) Solid state Nd:YAG laser cutting of CFRP sheet: influence of process parameters on kerf geometry and HAZ. 17th International Conference on Composite Materials (ICCM-17) Edinburgh, 10p
31. Patel RS (2016) Laser machining of CFRP. JEC composites magazine/No105, 46–49
32. Stock J, Zaeh MF, Conrad M (2012) Remote laser cutting of CFRP: improvements in the cut surface. Phys Procedia 39:161–170. https://doi.org/10.1016/j.phpro.2012.10.026
33. Yuji S, Masahiro T, Tatsuya N, Kasuki N (2013) Experimental study of CFRP cutting with nanosecond lasers. Trans JWRI 42(1):23–26
34. Shyha I (2013) An Investigation into CO_2 laser trimming of CFRP and GFRP composites. Proc Eng 63:931–937. https://doi.org/10.1016/j.proeng.2013.08.200
35. Hirsch P, Bastick S, Jeashke P, van den Aker R, Geyer A, Zscheyge M, Michel P (2018) Effect of thermal properties on laser cutting of continuous glass and carbon fiber-reinforced polyamide 6 composites. Mach Sci Technol:1–18. https://doi.org/10.1080/10910344.20181449216
36. Woon JK, Yousuki k, Seigi K (2013) Ultra high speed laser cutting using a scanner head. Trans JWRI 22(2):9–14
37. Wahab MS, Rahman NA, Mohamed MAS, Rahim EA (2014) Optimization of laser cutting parameters on the laminated carbon fibre reinforced plastics (CFRP) composites using DoE technique. Appl Mech Mater 660:60–64. https://doi.org/10.4028/www.scientific.net/AMM.6
38. Herzog D, Schmidt-Lehr M, Oberlander M, Canisius M, Radek M, Emmelmann C (2016) Laser cutting of carbon fiber plastics of high thickness. Mater Des 92:742–749. https://doi.org/10.1016/j.matdes.2015.12.056

39. Faas S, Freitag C, Boley S, Berger P, Weber R, Graf T (2017) Flow speed of the ablation vapors generated during laser drilling of CFRP with a continuous-wave laser beam. Appl Phys A 123:156. https://doi.org/10.1007/s00339-017-0781-0
40. Walter J, Hustedt M, Staehr R, Overmeyer L et al (2014) Laser cutting of carbon fiber reinforced plastics–investigation of hazardous process emissions. Phys Procedia 56:1153–1164. https://doi.org/10.1016/j.phpro.2014.08.030
41. Riveiro A, Quintero F, Lusquiños F, del Val J, Comesaña R, Boutinguiza M, Pou J (2017) Laser cutting of carbon fiber composite materials. Proc Manuf 13:388–395
42. Onuseita V, Prieß T, Wiedenmann M, Freitag C, Faisst B, Giedl-Wagner R, Rettich T, Weber R, Middendorf P, Graf T (2015) Productive laser processing of CFRP. Lasers in Manufacturing Conference 9p
43. Sun D, Han F, Ying W, Jin C (2018) Surface integrity of water jet guided laser machining of CFRP. Procedia CIRP 71:71–74. https://doi.org/10.1016/j.procir.2018.05.073
44. Hira H, Tsuboi A (2011) Study on cutting of CFRP plate by fiber laser. 18th International Conference on Composite Materials, 4 P
45. Bluemel S, Bastick S, Staehr R, Jaeschke P, Suttmann O, Overmeyer L (2016) Laser cutting of CFRP with a fibre guided high power nanosecond laser source – influence of the optical fibre diameter on quality and efficiency. Phys Procedia 83:328–335. https://doi.org/10.1016/j.phpro.2016.08.034
46. Pastras G, Fysikopoulos A, Stavropoulos P, Chryssolouris G (2014) An approach to modeling evaporation pulsed laser drilling and its energy efficiency. Int J Adv Manuf Technol 72:1227–1241. https://doi.org/10.1007/s00170-014-5668-z
47. Onuseita V, Weber R, Wiedenmanna M, Freitaga C, Grafa T (2014) Efficient laser processing of CFRP. 8th international conference on photonic technologies LANE 4p
48. Bluemel S, Kuklik J, Staehr R, Jaeschke P, Suttmann O, Overmeyer L (2017) Time resolved analysis of nanosecond pulsed laser processing of carbon fiber reinforced plastics. J Laser Appl 29:022406. https://doi.org/10.2351/1.4983242
49. Niino H, Harada Y, Anzai K, Matsushita M, Furukawa K, Nishino M, Fujisaki A, Miyato T (2016) Laser cutting of carbon fiber reinforced plastics (CFRP and CFRTP) by IR fiber laser irradiation. JLMN-J Laser Micro/Nanoeng 11(1):104–110
50. Xu H, Hu J (2017) Modeling of the material removal and heat affected zone formation in CFRP short pulsed laser processing. Appl Math Model 46:354–364. https://doi.org/10.1016/j.apm.2017.01.072
51. Salama A, Yan Y, Li L, Mativenga P, Whitehead D, Sabli A (2016c) Understanding the self-limiting effect in picosecond laser single and multiple parallel pass drilling/machining of CFRP composite and mild steel. Mater Des 107:461–469. https://doi.org/10.1016/j.matdes.2016.06.048
52. Liu Y-C, Chen-Wu W, Song H-W, Huang C-G (2016) Interaction between pulsed infrared Laser and carbon fiber reinforced polymer composite laminates. Proc SPIE 10152:id. 101520X, 6p. https://doi.org/10.1117/12.2246836
53. Ohkubo T, Tsukamoto M, Sato Y (2014) Numerical simulation of laser beam cutting of carbon fiber reinforced plastics. Phys Procedia 56:1165–1170. https://doi.org/10.1016/j.phpro.2014.08.031
54. Oberlander M, Bartsch K, Schulte C, Canisius M, Hergoss P, Herzog D, Emmelmann C (2017) Process monitoring of laser remote cutting of carbon fiber reinforced plastics by means of reflecting laser radiation. J Laser Appl 29(2):022009. https://doi.org/10.2351/1.4980165
55. Weber R, Hafner M, Michalowski A, Graf T (2011) Minimum damage in CFRP laser processing. Phys Procedia 12, Part B:302–307. https://doi.org/10.1016/j.phpro.2011.03.137
56. Wolynski A, Herrmann T, Mucha P, Haloui H, L'huillier J (2011) Laser ablation of CFRP using picosecond laser pulses at different wavelengths from UV to IR. Phys Procedia 12:292–301. https://doi.org/10.1016/j.phpro.2011.03.136
57. Stavropoulos P, Stournaras A, Salonitis K, Chryssolouris G (2010) Experimental and theoretical investigation of the ablation mechanisms during femtosecond laser machining. Int J Nanomanufacturing 6(1/2/3/4):55–65. https://doi.org/10.1504/IJNM.2010.034772