# RESEARCH PROGRESS ON THE QUALITY AND EFFICIENCY OF CARBON FIBER REINFORCED THERMOPLASTIC POLYMER COMPOSITES PROCESSED BY LASER

by

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*Carbon fiber reinforced plastics (CFRP) has been widely used in aerospace, military weapons, new energy and high-end vehicles due to its specific and superior strength, low density and long-lasting wear resistance. The processing of CFRP is very different from the traditional metal processing because of its heterogeneous structure, anisotropy and superior wear resistance of CFRP. Usually, CFRP has often various defects in mechanical processing and water jet processing, such as interlayer tearing, fiber pull-out, delamination, tool wear, and abrasive penetration. Through laser processing, the problems of CFRP materials existing in mechanical processing can be overcome. However, due to the huge differences in thermal physical properties such as thermal conductivity and vaporization temperature of carbon fiber and resin in CFRP, its laser processing also turns out to have some issues, such as heat-affected zone and fiber end expansion. This paper summarizes the research results of CFRP laser processing in China and internationally. Research progress was introduced in detail from various aspects including laser and material mechanism as well as laser processing parameters. It reports the experimental and theoretical studies covering the process accuracy in edge quality and the thermal characteristics in terms of heat-affected zone. Eliminating the heat-affected zone in the polymer matrix are considered the major obstacles of CFRP industrial applications. The methods of improving processing efficiency by increasing material removal rate and reducing processing time were reviewed. The influence of different thermal conductivity of carbon fiber and resin matrix in CFRP on the processing quality was discussed. Finally, the development trend and challenges of thermal conductivity of carbon fiber and resin in CFRP in theoretical modeling were proposed.*

Key words*: CFRP, laser processing, process parameters, heat-affected zone*

## Introduction

Carbon fiber reinforced plastics is composed of carbon fibers and resin matrix, in which carbon fibers mainly bear load and provide high strength for CFRP, while resin fills the void that is not occupied by carbon fibers and transfers the load on CFRP to them [1]. In CFRP, carbon fibers are orthogonally distributed in resin, and designers can conduct unidirec-

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tional multi-layer arrangement or multi-directional laminated arrangement according to the use requirements [2], as is shown in fig. 1. With the advantages of a high specific modulus, the high specific strength, a low density and an excellent wear resistance, CFRP has been widely used in aerospace, military weapons, new energy, high-end vehicles and rail transit [3, 4]. Most of the connection and assembly of these structures have requirements on precision coordination. Accordingly, there are high requirements for the machining quality and accuracy of the involved joints, holes and shapes, and the machined surface must be smooth without burrs, which also cannot be stratified [5]. A set of special tools and processes with a good machining efficiency have been formed during traditional machining. However, due to the anisotropy and heterogeneous structure of CFRP and the high hardness of carbon fibers, defects such as the delamination of machining surface, interlayer tearing, fiber pull-out and cutting-edge damage are prone to occur using traditional machining methods [6, 7], as is shown in fig. 2. In addition, there are also problems such as serious tool wear and chip pollution during machining [8]. Compared with mechanical processing, through water jet machining, tool wear can be reduced and there will be less thermal damage. But defects such as cutting surface delamination and incision deformation will be formed. In addition, the treatment and emission of water and abrasive slurry are not friendly to the environment [9].

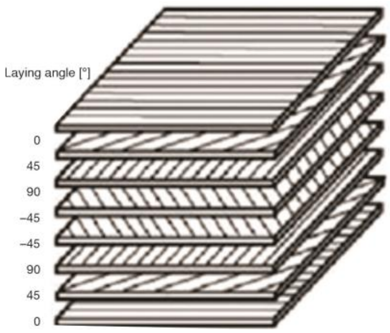


**Figure 1. Angle diagram of carbon fiber laying in CFRP laminates [10]**

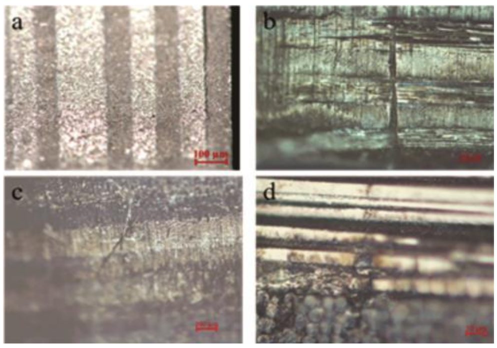


**Figure 2. Defects during the machining of CFRP [11]**

Compared with mechanical processing, laser processing has a lower cost, a higher precision and a better flexibility. In addition, as a non-contact processing, there are no problems caused by tool wear or contact force during laser processing, meanwhile chatter and vibration are also avoided [12]. These advantages make it a feasible alternative for high-precision machining of CFRP [13]. Although through the laser processing of CFRP, some problems during mechanical processing are solved, there are great differences in the thermal physical properties such as vaporization temperature, thermal conductivity and specific heat capacity between carbon fibers and resin matrix, and there are also great differences in the axial as well as radial thermal conductivity of carbon fibers [14], as is shown in tab. 1, which make the thermal input reactions caused by the two relatively high-power-density laser beams very different. On the one hand, the energy required for melting or vaporizing carbon fibers is higher than that required for melting or vaporizing resin matrix. On the other hand, the thermal conductivity of carbon fibers is much higher than that of resin matrix [15, 16]. Therefore, there are also some problems during the laser processing of CFRP, *e.g.*, defects such as heat-affected zones, burrs, delamination and fiber end expansion [17, 18], as is shown in fig. 3. Through a large number of theoretical and experimental verifications, scholars in

**Table 1. Thermophysical properties of carbon fibers and resin matrix**

| Parameter | Carbon fiber | Epoxy resin |
|---|---|---|
| Density [kgm$^{-3}$] | 1800 | 1200 |
| Specific heat capacity [Jkg$^{-1}$K$^{-1}$] | 753 | 1884 |
| Thermal conductivity [Wm$^{-1}$k$^{-1}$] | 50 (axial direction), 5 (radial direction) | 0.1 |
| Steaming temperature [K] | 3650 | 698 |
| Latent heat of phase change [KJkg$^{-1}$] | 43000 | 1000 |

China and abroad have found that by optimizing laser process parameters, the processing quality and efficiency can be effectively improved [19]. Therefore, the research results of domestic and foreign scholars on laser processing CFRP are reviewed in this paper, meanwhile the influence of laser processing parameters on processing quality and efficiency is summarized, providing a theoretical basis and technical guidance for the further development of laser processing CFRP.

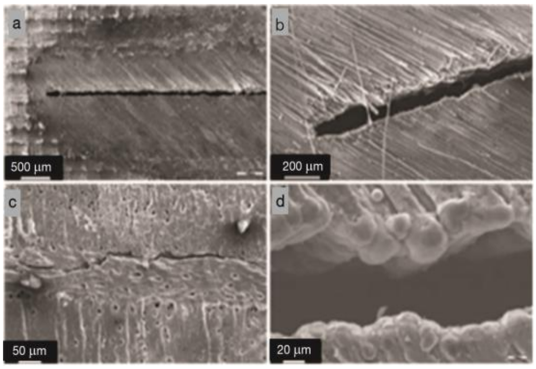

**Figure 3. Defects of laser processing CFRP [17]**

## Interaction mechanism between laser and materials

Laser processing is widely used in the complex processing of various materials, such as metals, alloys, ceramics and composites due to its particularity and advantages [20-22]. Laser processing is a kind of thermal processing technology, so its processing effect depends on the thermal physical properties of materials, rather than their mechanical properties [23-25]. During laser processing, the workpiece material surface absorbs parts of the heat generated by lasers incidents and transmits it to the workpiece interior. According to different laser power densities, the lasers melt, evaporate or chemically degrade parts of the processed materials to form an incision of a certain depth. At the same time, the materials are evaporated or melted by coaxial gas jet or recoil pressure, so that they are removed from the processing area [26].

The processing of CFRP materials is very different from that of traditional metals, which is caused by the uneven characteristics and anisotropy of matrix resin and carbon fibers [27]. In CFRP materials, the thermal conductivity and vaporization temperature of matrix resin are lower than those of carbon fibers. Therefore, during laser processing, before the carbon fibers reach the temperature that is needed for evaporation, the matrix resin evaporates first under the influence of laser energy [28]. Moreover, due to the thermal conductivity difference between carbon fibers and resin matrix, it is difficult to obtain laser processing CFRP materials of a better quality.

Laser machining is a promising alternative for traditional machining. However, laser processing is based on the thermal interaction between laser beams and CFRP, during which heat-affected zones will be produced. Due to the different thermophysical properties of carbon fibers and matrix resin in CFRP, the processing mechanism also depends on the laser source to a certain extent [29]. Pan and Hocheng [29] cut CFRP using fiber laser (frequency 300 Hz, power 350~650 W). It is found that the thermal conductivity of carbon fibers is different from that of matrix resin in CFRP (the thermal conductivity of carbon fibers is about 500 times that of resin). Therefore, a large amount of heat is transmitted and released to the resin through carbon fibers, resulting in defects such as matrix overheating, matrix degradation and heat-affected zones. Existing studies have shown that high-quality CFRP materials can be processed by lasers with a short wavelength [30]. Takahashi *et al*. [30] used Nd:YAG laser (UV and IR) to cut a 2 mm-thick CFRP plate. When the CFRP plate was irradiated by infrared laser, the laser directly heated the carbon fibers through the resin, while the ultraviolet laser only heated the resin surface, which had no obvious effect on the carbon fibers, as is shown in fig. 4. Leone and Genna [31] processed 1mm-thick CFRP with Nd:YAG laser (wavelength: 1064 nm, power: 150 W). Studies have shown that the laser processing of CFRP involves ablation, combustion and mechanical effect of different mechanisms.

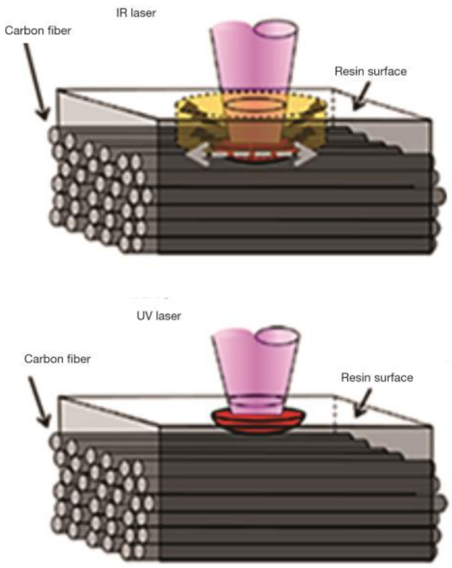

**Figure 4. Laser cutting process of CFRP [30]**

Laser radiation absorption is the most important phenomenon during the laser processing of CFRP, in which different effect is produced, such as heating, melting, evaporation and plasma ablation [20]. Through the interaction between CFRP materials and lasers, heat is generated and transmitted to remove the materials. Therefore, the removal mechanisms of CFRP materials and laser interaction are mainly thermal melting, thermal evaporation, photochemical reaction and so on.

## Machining quality

### *Structural characteristics of CFRP materials*

The CFRP is a heterogeneous anisotropic material, which is usually composed of several layers of carbon fibers cross arrangement. Due to the huge difference between thermal physical properties of matrix resin and carbon fibers, it is very difficult to process CFRP by lasers. In order to overcome this problem, many scholars have studied the properties of CFRP.

Stock *et al*. [32] added light-absorbing soot particles to the matrix resin, and cut 2.2 mm-thick CFRP using a 3 kW fiber laser. Compared with cutting experiments of ordinary CFRP, it was found that after adding light-absorbing soot particles, the absorption of lasers could be enhanced through matrix resin, the crack on the surface of the incision could be improved and a better cutting quality could be obtained.

Pan and Hocheng [33] showed that the size of heat-affected zones was affected by the orientation of carbon fibers during the laser slotting of unidirectional CFRP. When small heat-affected zones are produced through parallel-carbon-fiber-direction cutting, large heat-affected zones are produced through vertical-carbon-fiber-direction cutting. Wu *et al.* [34] also conducted similar studies and explained the damage mechanism of carbon fibers through different stacking methods. When the carbon fibers are arranged at 0°, the cutting taper is small, the cutting seam is rough, and the carbon fibers on both sides of the cross section of the cutting seam can be easily be exposed and pulled out, so the carbon fibers and matrix materials are easily removed at the same time. When the carbon fibers are arranged at 90°, the cutting seam is smooth, and the carbon fibers on both sides of the cross section of the cutting seam are not easily pulled out, which makes the carbon fibers difficult to be removed, meanwhile increasing the heat-affected zones, as is shown in fig. 5. When the arrangement position of carbon fibers is 45° or −45°, the carbon fibers on one side of the cross-section outlet of the cutting seam easily falls off, and those on the other side not easily fall off, as is shown in fig. 6. In addition, researchers have found that the physical properties of CFRP materials themselves have a certain impact on the quality of laser processing. Choi *et al*. [35] used picosecond lasers to process and compare thermosetting and thermoplastic CFRP materials. It is found that compared with thermosetting CFRP, thermoplastic CFRP is more sensitive to the heat generated by lasers, which requires a longer processing time, a lower power and a faster scanning speed.

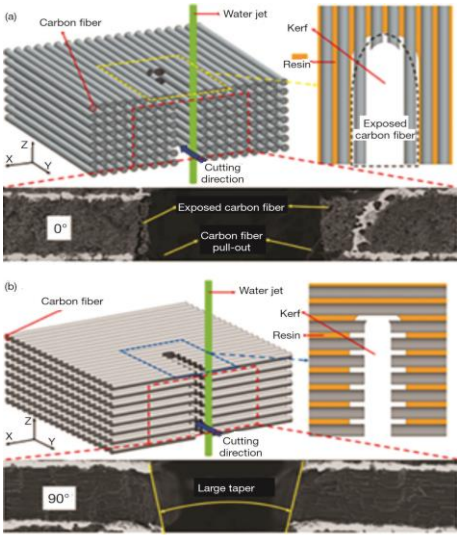


**Figure 5. Carbon fiber arrangement model and physical drawing; (a) 0° arrangement and (b) 90° arrangement [34]**

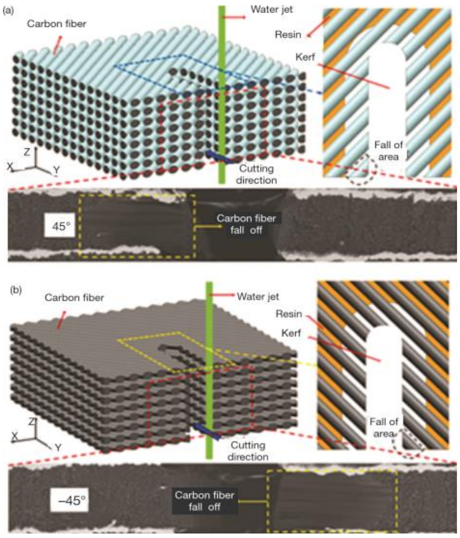


**Figure 6. Carbon fiber arrangement model and physical drawing; (a) 45° arrangement and (b) −45° arrangement [34]**

### *Laser parameters*

#### *Laser wavelength*

The CFRP has different absorption rates for lasers of different wavelengths. A shorter wavelength can be highly absorbed by materials due to the higher photon energy. In addition, through the use of shorter-wavelength lasers, smaller spot sizes can be achieved. Lasers can be divided into infrared lasers, visible light and ultraviolet lasers according to their wavelength [36]. Laser wavelength plays an important role in the processing quality of CFRP materials. Leone *et al*. [37] used Yb:YAG laser to process CFRP, who found that the wavelength had a significant influence on the expansion of the heat-affected zones during CFRP laser processing. The photon energy of a long wavelength (IR) is low, which is not sufficient to decompose CFRP materials, while that of a short wavelength (UV) is high, which is sufficient to decompose CFRP materials.

Sato *et al*. [38] compared two nanosecond lasers of different wavelengths (1064 nm, 266 nm), cutting a 0.6 mm-thick CFRP plate using the same parameters (power density: $4.7 \cdot 10^9$ W/cm$^2$, pulse width: 6 ns, frequency: 10 Hz, spot size: 100 μm, scanning speed: 1 mm/s). The cutting rate of the infrared laser at 1064 nm was 0.85 μm/pulse, while that of the ultraviolet laser at 266 nm was 0.60 μm/pulse. However, the heat-affected zone of 1064 nm infrared laser was 105 μm, while that of 266 nm ultraviolet laser was 88 μm. The cutting speed of 1064 nm was higher than that of 266 nm, although the heat-affected zone of 1064 nm was greater than that of 266 nm.

Takahashi *et al*. [30] used infrared laser (IR, wavelength 266 nm) and ultraviolet laser (UV, wavelength 1064 nm) Nd:YAG laser to process CFRP materials, who established a heat conduction model to study the effect of wavelength on processing quality. The results show that there was a smaller heat-affected zone in UV-laser-processed CFRP materials with a better surface quality. At the same time, through SEM observation and finite element model calculation, there was resin residual near the incision processed by UV laser, and almost all the resin at the incision processed by infrared laser was removed, as is shown in fig. 7, which proves that the heat-affected zone during UV laser processing is smaller than that during infrared laser processing.

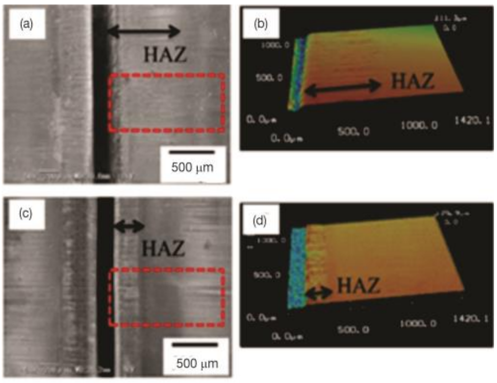


**Figure 7. Top surface; (a) and (c) SEM and (b) and (d) CSLM images of CFRP substrates scanned with IR (a) and (b) and UV (c) and (d) lasers [30]**

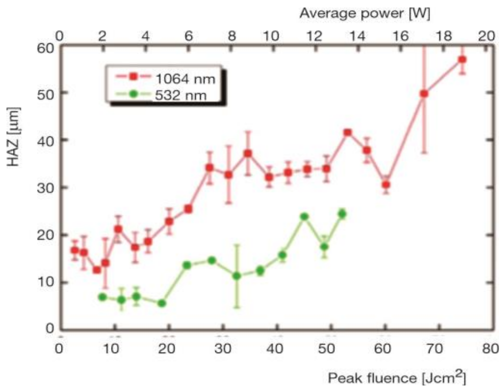


**Figure 8. Heat-affected zones of laser ablation at different wavelengths [39]**

Wolynski *et al*. [39] used picosecond laser systems operated at different wavelengths (355 nm, 532 nm, and 1064 nm) to experimentally study the processing quality and processing time of CFRP. The results show that the heat-affected zone at 1064 nm was larger than that at 532 nm, which had a linear relationship with the power, as is shown in fig. 8. Therefore, for picosecond lasers, the decrease of wavelength means the increase of local energy [40, 41], which is conducive to the simultaneous removal of carbon fibers and resin matrix during processing, avoiding the phenomenon that resin matrix is removed while carbon fibers are remained, indirectly leading to the reduction of heat-affected zones.

### *Pulse width*

According to different pulse widths, lasers can be divided into nanosecond lasers, picosecond lasers and femtosecond lasers. Since the heat-affected zones are affected by the interaction time between lasers and materials, short-pulse lasers are a choice to reduce the interaction time between lasers and materials. At the same time, the plume generated by pulse action can also be used to remove residual materials and improve the processing quality. Therefore, through the use of ultra-short pulse lasers, such as femtosecond and picosecond lasers, high pulse energy can be released in a very short period of time, so that the materials directly evaporate due to the laser beams, and there is almost no time for heat to spread to adjacent materials, which limits the expansion of the heat-affected zones and improves the processing quality of CFRP [42, 43].

Xu *et al*. [44] used Nd:YVO4 laser systems with different pulse widths to cut CFRP with a thickness of 2 mm. It is found that with the shortening of pulse width, the ablation depth increases, while the heat-affected zones decrease significantly, as is shown in fig. 9. Emmelmann *et al*. [45] processed a square cavity in CFRP laminates using two lasers with different pulse widths (a nanosecond laser and a picosecond laser), and analyzed the extension of the heat-affected zone at the edge of the cavity during laser ablation of CFRP laminates. They concluded that the pulse width had a significant impact on the quality of CFRP processing, the shorter the pulse width was, the smaller the heat-affected zone would be. Ye *et al*. [46] used a microsecond laser, a nanosecond laser and a picosecond laser to process CFRP, who reached a conclusion similar to that of Emmelmann's, that is, the heat-affected zone increased with the increase of pulse width, as is shown in fig. 10.

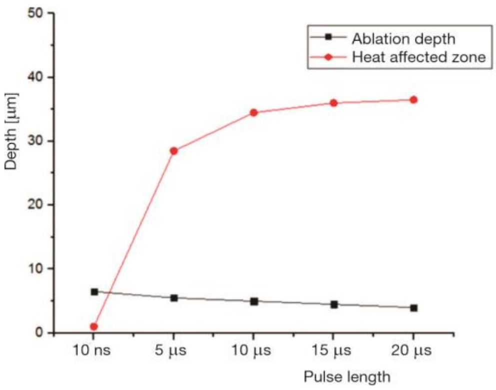


**Figure 9. Ablation depths and heat-affected zones under different pulse widths [44]**

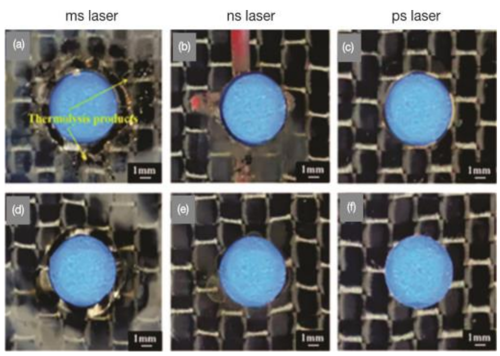


**Figure 10. Surface morphology around the hole inlet (a)-(c) and hole outlet (d)-(f) [46]**

Therefore, using a picosecond laser system to process CFRP, smaller heat-affected zones can be produced compared with traditional nanosecond lasers. Freitag *et al*. [47] used an infrared picosecond laser to cut 2 mm-thick CFRP, obtaining a heat-affected zone of less than 20 μm, the effective cutting speed reached 0.9 μm per minute. Compared with picosecond lasers, femtosecond lasers have smaller pulse intervals, through which CFRP processing can be realized with a higher precision and smaller thermal effect. Jiang *et al*. [48] used an infrared femtosecond laser with a maximum power of 10 W to drill a CFRP plate with a thickness of 2 mm, obtaining a heat-affected zone of less than 10 μm, which fully demonstrated the advantages of ultrafast laser processing of CFRP. Therefore, the pulse width has a significant impact on the processing quality of CFRP, and a shorter pulse width can significantly reduce the heat-affected zones [49, 50].

In summary, with the increase of pulse width, the heat-affected zones increase. This is mainly due to the decrease of power density and the increase of the interaction time between lasers and materials, resulting in more heat transfer to the internal CFRP through heat conduction, together with the damage of the resin, rather than the removal of the materials, thereby increasing the heat-affected zones. Therefore, through the ultra-short pulse laser processing of CFRP, smaller heat-affected zones can be obtained.

*Pulse energy*

The melting point of carbon fibers in CFRP materials is generally 3500 °C, while that of resin matrix is generally only 200-350 °C. The difference between them is significant, which leads to that in laser processing, if the pulse energy is not enough to make carbon fibers reach their melting point, the resin matrix on their surface will be removed and the processing effect cannot be achieved [51, 52]. However, excessive pulse energy will affect the non-processing areas of the materials, resulting in the expansion of heat-affected zones and an excessive heat storage, which will damage the processed materials [53].

Salama *et al*. [54] used an infrared picosecond laser to drill 6mm-thick CFRP, who obtained a heat-affected zone of less than 25 μm. They found that with the decrease of pulse energy and the increase of scanning speed, the size and etching depth of the heat-affected zone decreased, as is shown in fig. 11. Wahab *et al*. [55] used a Nd:YAG laser to cut 1.5 mm-thick CFRP, who also studied the influence of pulse energy on the heat-affected zone. It is concluded that heat-affected zones increase with the increase of pulse energy, as is shown in fig. 12.

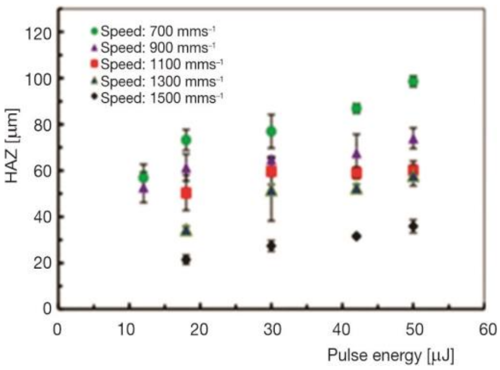


**Figure 11. Effect of pulse energy on heat-affected zones at different scanning speeds [54]**

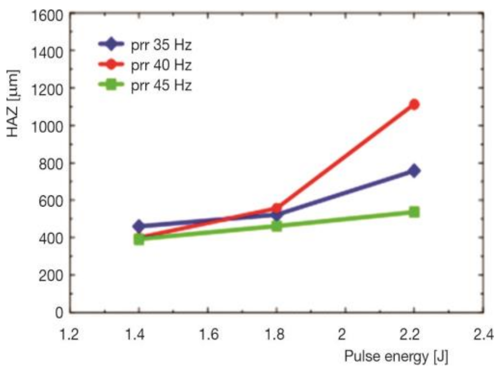


**Figure 12. Effect of pulse energy on heat-affected zones at different frequencies [55]**

Oliveira *et al*. [51] used a femtosecond laser with the pulse energy of 0.1-0.5 mJ to cut CFRP plates. It can be clearly seen from fig. 13 that when the pulse energy was 0.13 mJ and 0.18 mJ, only the resin matrix was removed by the laser, while the carbon fibers were exposed. When the pulse energy was 0.26 mJ and 0.40 mJ, the resin and carbon fibers were ablated. Xu *et al*. [49] Used a Nd:YVO4 nanosecond laser to cut CFRP plates. Four groups of pulses with different energy were set between 5 W and 20 W, and the conclusion was similar to that of Oliveira *et al*., [51] that is, the processing quality decreased with the increase of pulse energy. As is shown in fig. 14, on the cutting surfaces of 0.4 mJ, 0.6 mJ, and 0.8 mJ, there is a large amount of resin matrix stripping, with even carbon fiber breakage and extraction. On the cutting surface of 0.2 mJ, only a small amount of resin stripping occurs, and the fibers are not exposed, which are intact. Therefore, under the premise of meeting the cutting requirements, the pulse energy should be reduced as much as possible during the laser processing of CFRP materials.

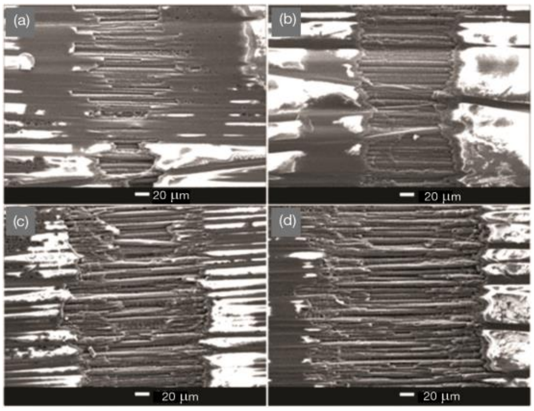


**Figure 13. The SEM under different pulse energy; (a) 0.13 mJ, (b) 0.18 mJ, (c) 0.26 mJ, and (d) 0.40 mJ [51]**

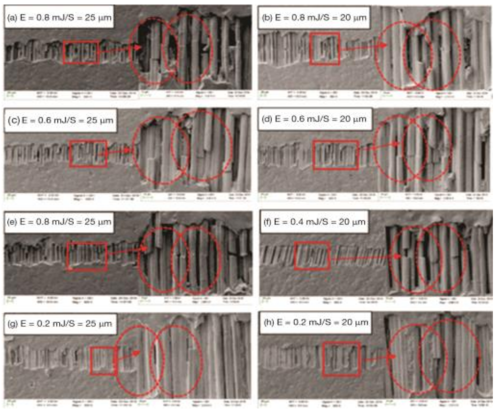


**Figure 14. Surface morphology of laser ablation CFRP under the SEM [49]**

*Scanning speed*

By increasing the laser scanning speed, the pulse overlap, the heat accumulation effect and the heat-affected zones can be reduced meanwhile improving the processing quality. However, due to the self-limitation during laser processing, when the scanning speed reaches a certain value, it will continue increasing, without leading to a great impact on the size of the heat-affected zones. Therefore, an appropriate scanning speed should be chosen during the actual processing, so as to achieve the optimal processing quality and efficiency.

Li *et al*. [56] used an IPG YLS-5000 laser to drill 2 mm-thick CFRP plates, and three scanning speeds were set, namely 500 mm per minute, 800 mm per minute, and 1100 mm per minute. The results showed that the corresponding heat-affected zones were 17.5 $mm^2$, 11 $mm^2$, and 9 $mm^2$ respectively. However, another study shows that the heat-affected zones produced at a scanning speed of 1500 mm per minute are slightly higher than that at 1000 mm per minute when CFRP plates with a thickness of 2 mm are drilled by lasers, which proves the self-limitation of laser-processing CFRP composites. Gautam *et al.* [57] also reached a similar conclusion. When drilling 3.5 mm-thick CFRP plates with lasers, the influence of scanning speed on the heat-affected zones is becoming less and less obvious with its increase. When the scanning speed reaches 280 mm/s, it is difficult to continue increasing and the heat-affected zones are narrowed. The influence of scanning speed on the cutting quality of the hole wall cannot be ignored. Figure 15 shows the surface morphology of the holes under a SEM at different cutting speeds. It can be seen that when the scanning speed is low, stripes and small holes may appear on the hole wall, which is detrimental to the strength after machining.

In addition, Takahashi *et al*. [58] proposed and studied the joint effect and influence of scanning speed as well as spacing on machining quality. The results show that the machining quality mainly depends on the scanning distance. With the increase of the scanning distance at each scanning speed, the machining quality is improved, which is because under a non-zero scanning distance, lasers can easily enter the grooves on the material surface, so that the machining can be completed by carbon fibers with a high speed and quality. Too high scanning speeds will not only cause self-limiting effect, making the cutting quality unable to continue increasing, but the processing time will also increase. Therefore, it is necessary to find out the optimal scanning speed during processing through experiments.

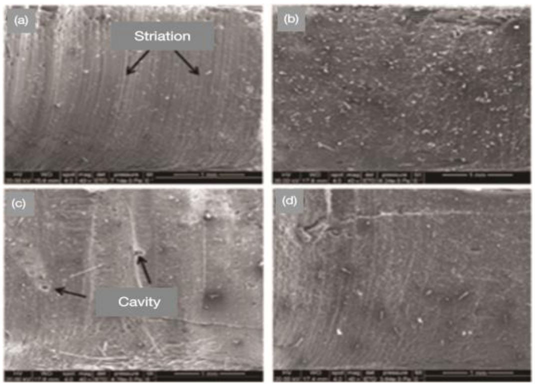


**Figure 15. The pore surface morphology at different scanning speeds; (a) and (c) 500 mm/min and (b) and (d) 1500 mm/min [53]**

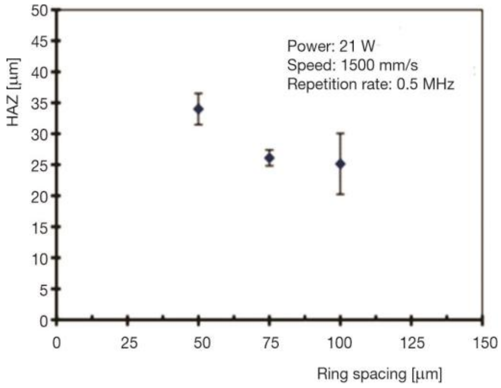


**Figure 16. Effect of ring spacing on heat-affected zone [54]**

### ***Process strategy***

*Scan path*

Li *et al.* [59] studied the processing quality of CFRP using a solid-state ultraviolet laser with a diode light source, who first proposed a new CFRP laser processing method and used multiple rings to expand the cutting incision, so as to remove the material more effectively.

Salama *et al.* [54] used a multi-loop strategy to remove the materials and to expand the incision at the beam entrance, thereby reducing the plume generated during CFRP laser processing to shield incident lasers. They used a 400 W picosecond laser to drill 6mm-diameter holes on 6mm-thick CFRP, and the scanning speed was 1500 mm/s. It can be clearly seen from fig. 16 that the heat-affected zone has been significantly improved by increasing the ring spacing.

Salama *et al.* [60] studied the influence of multi-loop strategy on the processing time and quality of CFRP materials, who proposed the self-limiting effect of laser processing. They first studied ring spacing and found that incision depth increased with the increase of ring spacing. However, when ring spacing was larger than the diameter of the focused laser spots, the rings became independent and the materials of the incision could not be completely eliminated. Although the machining depth is very deep when the ring spacing is greater than 50 μm, there are residual materials among the rings. Therefore, the ring spacing of 30 μm is the best. The ring spacing was fixed to 30 μm, and the same total energy was provided to the specimen processing area. The single-ring and multi-ring processing strategies were compared, as is shown in fig. 17. The results show that there is *self-limiting effect* during laser processing (even if additional laser energy is transferred to the processing areas, the processing depth will be limited), so with the use of multiple rings, deeper grooves will be produced compared with the use of single rings, which greatly improves the processing speed.

*Gas-liquid assistance*

During the laser processing of CFRP materials, inert gases such as argon are often used to suppress the heat conduction and lessen fiber damage during processing, so as to improve the surface processing quality. Riveiro *et al.* [19] compared the effect of conventional-convergent-jet- or supersonic-jet-assisted laser processing on the processing quality of

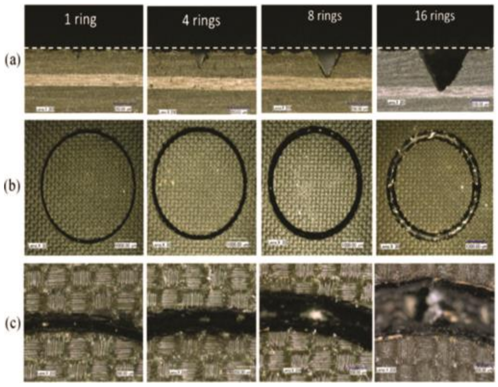


**Figure 17. Microscopic photographs of ring number effect; (a) cross-section, (b) top surface, and (c) top feature view [60]**

CFRP. It was found that the size of the heat-affected zones produced in the two cases was almost the same, but the removal rate of matrix and fiber was higher when a supersonic jet was used. Zhao *et al*. [61] compared the effect of static air, static nitrogen, open air and supersonic air-flow on the processing quality of laser processing CFRP materials. The results show that the ablation rate of laser-processed materials assisted by supersonic air-flow is more than twice that of it under ablation mode, and the machined surface is smoother. This means that the thermomechanical erosion caused by tangential supersonic air-flow plays an important role in laser ablation process.

The application of ultrasonic jet gas to the laser processing of CFRP materials is a double-edged sword. Not only can the high ablation rate brought by supersonic air-flow be used to improve the processing efficiency, but excessive heat-affected zones can also be avoided to reduce the processing quality. This needs to be comprehensively considered in the selection of process parameters, and further research is still needed at this stage.

When using water-jet-guided laser processing technology to process CFRP materials, the heat on the material surface can be quickly cooled through a water jet, taking away the processing residue and cleaning the heat-free zones around the holes, which has a good processing effect. Zhang *et al*. [62] used a Nd:YAG laser assisted by a water jet system to cut 2 mm-thick CFRP. Figure 18 shows the temperature field after processing 0.1 ms with or without the water jet. Without the action of a water jet, the laser energy follows a Gaussian distribution, and the heat transfer process of the lasers acting on each layer of carbon fibers is anisotropic. The performance of heat transfer along the direction of carbon fibers is better, and that perpendicular to the direction of carbon fibers is poor, which leads to an obvious heat storage and a rapid removal of the materials. Therefore, the temperature distribution on the carbon fiber layer is elliptical, which indicates that the traditional laser processing of CFRP will lead to holes of incomplete shapes and affect the processing effect. During laser pro-

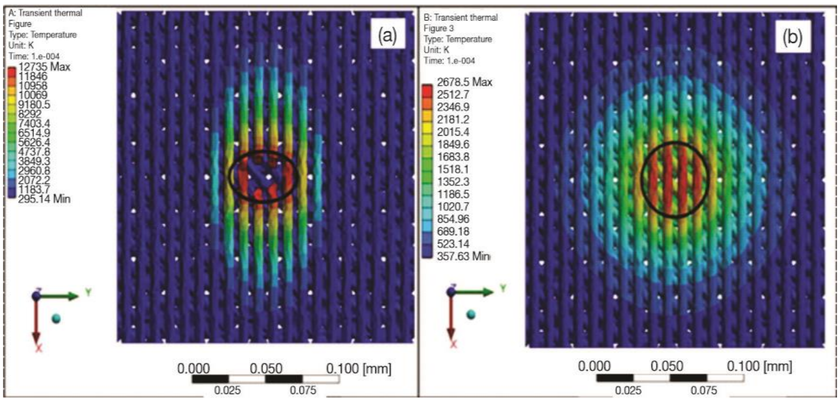


**Figure 18. Temperature field distribution; (a) anhydrous jet assistance and (b) water jet auxiliary [62]**

cessing of a water jet, the distribution of laser energy is changed to a uniform distribution by the water jet, and the temperature distribution on the carbon fiber layer is circular, which shows that the temperature distribution is uniform and the heat-affected zones are small, thus obtaining a better processing quality.

In summary, although the essence of gas- and liquid-assisted machining is to reduce the influence of heat-affected zones on CFRP materials and improve the processing quality, the cold and heat balance of the processing areas cannot be controlled, which will cause unnecessary heat loss and reduce the processing efficiency. Therefore, during actual processing, in order to achieve both processing efficiency and quality, it is necessary to comprehensively select an appropriate auxiliary means to achieve an accurate control of heat and cold balance.

## Working efficiency

For industrial applications, one of the most important evaluation criteria is processing efficiency. Different laser processing parameters have obvious influence on not only the processing quality of CFRP materials, but also the processing efficiency. Wolynski *et al.* [39] processed CFRP with a picosecond laser, and studied the effect of different processing parameters on the removal rate of CFRP. Figure 19 shows the relationship between different laser powers and material removal rates with all the three laser wavelengths. It can be seen that the material removal rate and power increase approximately linearly. However, for lasers of the three different wavelengths, the material removal rate can be significantly improved by increasing laser energy, which helps to improve the efficiency of laser processing of CFRP materials. Finger *et al.* [42] found the same phenomenon when using picosecond UV-laser-processing CFRP materials. In addition, it is also found that with the same laser energy, reducing the scanning speed is also conducive to the increase of material removal rate. For a 67.6 W picosecond UV-laser, when the scanning speed decreases from 10 m/s to 1 m/s, the material removal rate increases from 50 $mm^3$ per minute to 100 $mm^3$ per minute. However, if reducing the scanning speed, the range of heat-affected zones will increase. Therefore, it is necessary to comprehensively consider the influence of both in practical engineering. Niino *et al.* [63] used a CW near-infrared laser with an average power of 2-3 kW to cut a CFRTP-ABS plate and a CFRTP-PPS plate with a thickness of 3 mm. The research shows that at the speed of 3.6 mm/s, the complete cutting of a CFRTP-PPS plate and a CFRTP-ABS plate requires 27 and 15 laser irradiations, respectively. This shows that the cutting time of CFRTP-PPS plates is almost doubled, while the processing efficiency is reduced by nearly 50%.

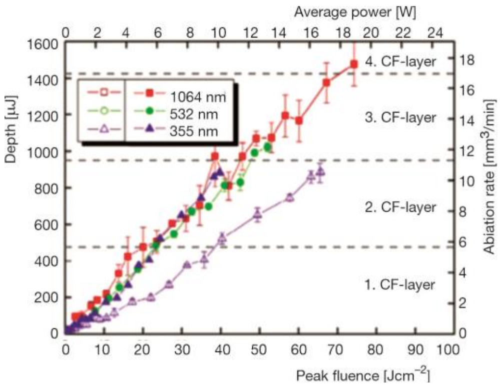


**Figure 19. Material removal rate and machining depth of CFRP processed by lasers with different wavelengths [39]**

Finger *et al.* [42] and Salama *et al.* [54] found similar phenomena when respectively using picosecond ultraviolet lasers and nanosecond infrared lasers to process CFRP materials. Goeke *et al.* [64] also found that for the same laser, with the increase of laser energy, processing depth would also significantly increase. For both fiber lasers and $CO_2$ lasers, by increasing the power, the machining depth can be increased. However, when the laser power increases to a certain extent, the further increase of power has little effect on the machining depth, which is also due to the self-limiting effect of CFRP composites during laser processing.

In general, by reducing the laser scanning speed or increasing the laser power, the laser processing efficiency will be greatly improved. However, such improvement will also have self-limiting effect. When the process parameters reach a certain degree, the improvement of processing efficiency is not obvious. In addition, increasing laser power may lead to the expansion of heat-affected zones, which is unfavorable to the processing quality. Therefore, in practical engineering, the processing quality and efficiency should be considered to determine the process parameters.

## Summary and prospect

The thermal physical properties of carbon fibers and resin matrix in CFRP are greatly different, which makes laser processing a great challenge. Heat-affected zones usually appear during the laser processing of CFRP materials. Therefore, reducing and eliminating heat-affected zones is a key issue in the laser processing of CFRP materials. In order to study the influence of different process parameters on the quality and efficiency of CFRP laser processing, scholars have used different types of lasers (such as $CO_2$, Nd:YAG, excimer and fiber lasers) to carry out various studies. Studies have shown that in order to reduce the heat-affected zones, it is recommended to use single pulses with low energy, short pulse widths, high scanning speeds and high-pressure auxiliary gas. For example, using ultra-short-pulse lasers (such as femtosecond lasers) to shorten the interaction time between lasers and materials, heat-affected zones can be reduced and the machining quality can be improved. In addition, with the multi-ring laser technology, the self-limiting effect during laser processing can be slowed down, significantly improving the processing quality (heat-affected zones < 10μm) and efficiency. However, in the current laser processing of CFRP, there are still many problems to be further studied.

- The CFRP has the best wavelength absorption of $CO_2$ lasers, but research on the $CO_2$ laser machining modeling of CFRP is very limited. If the theoretical or finite element model analysis is established, it will help to further understand the problems in the machining process. In addition, it is necessary to develop a plasma dynamics model for femtosecond laser processing of CFRP materials and laser interaction, so as to further understand and improve processing quality and efficiency.
- Future research directions can also start from theoretical modeling and simulation. Since the thermal conductivity of carbon fibers and resin in CFRP is greatly different, and that of carbon fibers varies with temperature, it is difficult to consider this change during theoretical modeling.
- Ultra-short-pulse laser processing CFRP, although obtaining a high processing quality, has a low processing efficiency. Therefore, it is necessary to find a way to achieve high-efficiency processing.
- Due to the difference in thermal physical properties between carbon fibers and resin matrix of CFRP, laser processing of CFRP is difficult. It can be further studied from the perspective of balancing the differences between the thermophysical properties of the two, so as to achieve the purpose of a high quality and efficiency.
- The contribution of laser ablation stage and mechanical erosion caused by polymer pyrolysis was studied using two adjacent laser pulses or two parallel lines.

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