LASER MACHINING OF CFRP

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ABSTRACT

The use of Carbon-Fiber Reinforced Polymer (CFRP) is becoming more widespread across various industries such as, aerospace, automotive, wind energy, oil & gas exploration and sports equipment. As applications are on the rise, so too are the needs to cut, drill, texture, and otherwise fabricate the material. The attributes that make CFRP a very unique and useful material also make it difficult to machine with high quality. Because the high strength of the carbon fibers causes excessive wear to mechanical tooling and abrasive waterjet technique can potentially damage fiber and causes yield loss, researchers are increasingly looking towards other technologies including lasers. Furthermore, the broadening application space has created the need for finer features and more intricate cutting patterns – both of which are traditional strengths of laser processing. Processing using high power infrared (IR) lasers has shown that high speeds can be achieved; however, quality usually suffers due to large heat affected zone (HAZ). While quality can be improved by using ultrashort pulse lasers, this comes with the cost of lower processing speed. In this work, we demonstrate laser processing of CFRP with a high power, hybrid fiber laser operating at an ultraviolet (UV) wavelength of 355 nm with an average power of 60 W. Laser parameters have been optimized to develop cutting, drilling, and surface texturing processes that delivers both high processing speed and quality. The optimization of parameters – including those enabled by the unique TimeShift™ pulse-shaping technology – results in lateral HAZ dimensions of only 10-20 μm at higher machining speeds.

1 INTRODUCTION

Carbon Fiber Reinforced Polymers or Plastics (CFRP) are being used widely today in many industries. A strong desire to increase fuel efficiency and reduce carbon emissions in aerospace and automotive industries is driving the use of CFRP material in the fabrication of various aircraft and automobile parts. For automobiles a 10% reduction in weight typically leads to 6% to 8% reduction in fuel consumption. The corporate average fuel economy (CAFE) standards in the US will require auto manufacturers to achieve a fleet average of 54.5 miles per gallon by 2025. In the European Union, CO_2 emissions limits for passenger cars are reduced from 130 gm of CO_2/km in 2015 to a much more challenging 95 gm of CO_2/km by 2020 [1]. CFRP is a lightweight, strong, durable material with good corrosion and vibration resistance. CFRP is a good candidate to replace many metal parts. An optimally designed CFRP part can be up to 70% lighter than steel and 30% lighter than aluminium [2]. These attributes are what makes CFRP attractive also for use in many non-transportation related industries such as components for wind energy production, sports equipment, oil exploration equipment, and even in some consumer electronics products as well.

The attributes that make CFRP a very unique and useful material also make it difficult to machine with high quality. Manufacturers using CFRP in their products are also looking to decrease fabrication costs. In addition, as the material cost continues to decline, demand and use for CFRP material overall will further increase.

Among the currently practiced CFRP machining techniques, a conventional mechanical machining technique is costly due to high tool wear and operating costs. Also, fiber fracture and delamination of material during machining is common and results in yield loss. The more commonly used abrasive waterjet technique does provide high quality machining without any thermal damage. However, it is a very noisy process with potential for fiber damage due to high pressure jet and provides opportunity for water and abrasive particles to get trapped in the material which can lead to yield loss. While use of lasers for machining CFRP is in its early stages, lasers have been successfully adopted in manufacturing industry for machining various metals. The use of lasers for machining provides the advantages of a non-contact process and ease of automation in manufacturing environments. Laser machining also eliminates tool wear and reduces operating costs in general. It also eliminates gradual degradation in quality associated with mechanical techniques due to tool wear. In addition, using lasers for CFRP machining fiber damage and delamination of material during machining can be reduced or eliminated. However, there is a key challenge for laser machining of CFRP, which is to machine it with both high throughput and with minimal heat affected zone (HAZ) formation in the material.

2 LASER CHOICES

The most fundamental challenge for laser machining CFRP stems from the fact that it is a non-homogeneous material mixture of carbon fibers and an organic polymer matrix. The optical and thermal properties of fiber and polymer are vastly different and hence the interaction of each material with laser is very different. Even more difficult is that the optical and thermal properties of carbon fiber are anisotropic and vary widely along the fiber axis and perpendicular to the fiber axis. These fundamental material properties creates a challenge to define a set of laser parameters that can provide good quality high speed machining of CFRP in all directions.

High power continuous wave infrared wavelength lasers with multi-kilowatt power levels can machine CFRP at higher speeds but leave the material with unacceptably large HAZ [3-5]. One way to reduce large HAZ is to add delay time intervals between machining steps but that adds to overall processing time and hence reduces throughput. On the other hand, ultrashort pulse lasers with pulse widths in the picosecond and femtosecond range can provide low HAZ but usually machine materials at slow speeds [6-8]. To improve machining speed very high power ultrashort pulse lasers are needed. While research on developing higher power ultrashort lasers is ongoing it may be difficult to realize a source that is cost effective and practical for a 24/7 manufacturing use. So, the current challenge is to find a laser source and process that can deliver a good balance of speed and quality. Pulsed nanosecond (ns) lasers thus far have shown moderate processing speeds with reasonable quality, with the wavelength often having a significant impact on results achieved. In particular, the stronger absorption at ultraviolet (UV) wavelength results in good quality machining. The machining results achieved using a nanosecond pulsed UV laser is a strong function of average laser power, pulse width, and pulse repetition frequency (PRF). The higher average power and PRF helps achieve higher machining speed, while lower pulse width results in higher quality machining.

Traditional diode pumped solid state (DPSS) Q-Switched pulsed UV nanosecond lasers typically have a constant, non-adjustable pulse width at a given PRF. While PRFs on such lasers are adjustable, output power decreases and pulse width increases by a lot with increase in PRFs. Typically, higher power and shorter pulse widths are available only at lower PRFs. This significantly limits the ability of the laser to be operated at higher PRF affecting the micromachining speed, feature size, accuracy and quality achieved. Also typical Q-Switched lasers do not have pulse shaping and pulse splitting capability which can help improve the micromachining quality and throughput. To overcome these limitations, in 2013 we at Spectra-Physics® introduced Quasar® 355-40, a breakthrough new 355 nm wavelength UV pulsed hybrid fiber laser, shown in Figure 1. It is a laser with a unique combination of higher power and shorter pulse width available at higher PRF. Quasar also offers TimeShift™ technology for software adjustable energy and intensity manipulation of pulses in the time domain such as, pulse shaping, pulse splitting, and burst mode operation. The current model, Quasar 355-60, with an output power of >60 W at 300 kHz PRF, offers the highest power available today in the market at higher repetition rates with single mode beam quality.

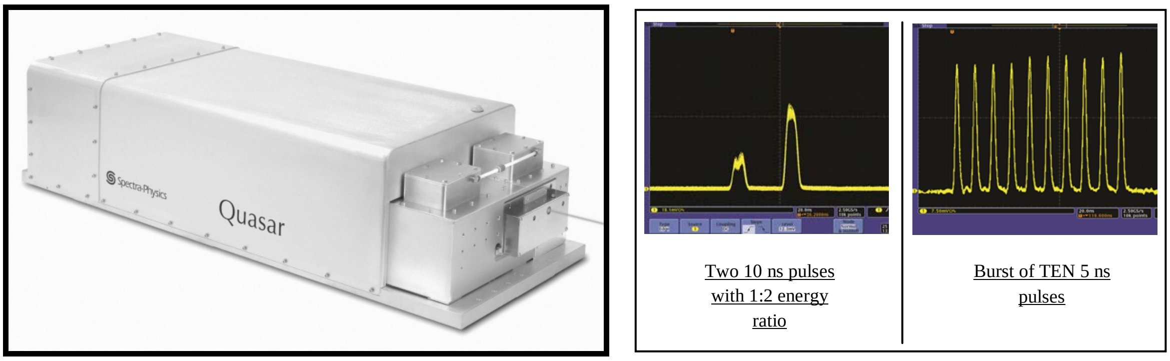
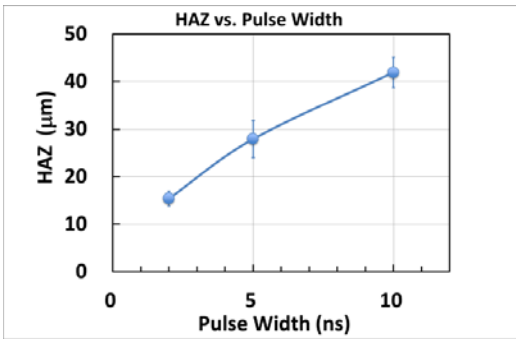


Figure 1: The Quasar laser and examples of TimeShift technology which enables pulse shaping, pulse splitting, and burst mode operation.

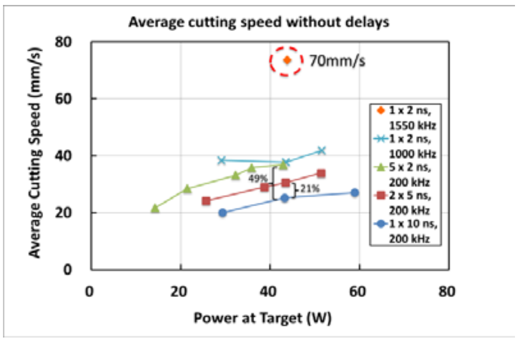
3 CFRP CUTTING

To demonstrate the capability of the Quasar 355-60 laser cutting we machined 250 μm thick PAN-based unidirectional CFRP plate material. We varied the laser pulse width, power, repetition rate, and scanning speed. We also tested the burst machining capability provided by Quasar's TimeShift technology. The cutting speed and heat affected zone (HAZ), here defined as the average length of exposed fibers along the cut line, were characterized for various conditions.

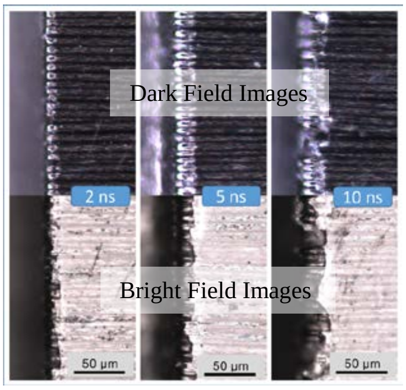
The results in Figure 2 show that smallest HAZ of ~15 μm was achieved using 2 ns pulses. This is an average HAZ over a number of process conditions, and in some cases the HAZ was effectively zero. Burst machining proved to be advantageous, achieving approximately 20 to 50% higher cutting speeds for the same average power. More details of burst machining advantages can be found in [9]. Through additional process development and optimization efforts we have shown that the Quasar can cut 250 μm thick CFRP plates at 70 mm/sec with HAZ of < 15 μm.



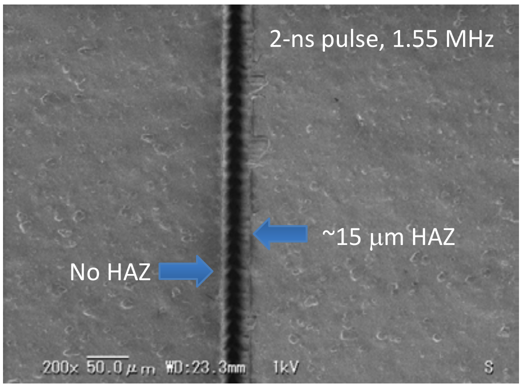
(a)



(b)



(c)



(d)

Figure 2: (a) Effect of pulse duration on HAZ, (b) Effect of power, repetition rate, and pulse duration (including burst of pulses) on cutting speed, (c) Optical micrographs show matrix chipping/exposed fibers and underlying HAZ for 2, 5, and 10 ns pulse widths, and (d) SEM image of CFRP sample.

Using the optimized laser process parameters we were also successful in cutting thicker ~1mm thick cross weaved CFRP plate as shown in Figure 3.

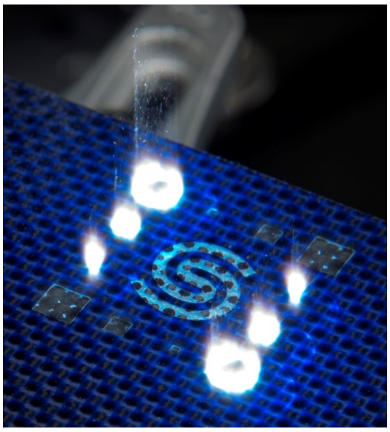


Figure 3: The Spectra-Physics logo and other features machined in ~1 mm thick CFRP plate.

4 CFRP DRILLING

The drilling of CFRP parts is also a very important process since traditional riveting and other types of fastening techniques requires drilling holes in the material. The mechanical and waterjet processes can be detrimental to the strength of the part due to fiber damage during the drilling process. The fiber damage can ultimately lead to a weaker structure. The process parameters developed for cutting can be effectively used for trepan drilling holes in CFRP as shown in Figure 4.

Figure 4: Picture above shows surface texturing (Spectra-Physics logo and square features at the top and bottom of the sample) and hole drilling in CFRP without any visible fiber damage using Quasar UV laser.

4 CFRP SURFACE CLEANIGN AND TEXTURING

A well-developed joining technique for CFRP parts is essential to fully utilize its potential to manufacture large parts in aerospace and automotive industry. A robust adhesive joining process has to be developed to fully allow design engineers utilize advantages offered by CFRP material. The traditional bolting and riveting joining techniques can be made to work using lasers, instead of mechanical tools, to drill holes and avoid fiber damage. However, large numbers of holes are needed to join large parts and adhesive joining can be economical compared to laser drilling holes. Besides, adhesive joining provides more efficient load management, so the thickness and weight of the part can be reduced. Also, it is possible that bolting or riveting may not be an option in some cases for parts due to its design. For adhesive joining, CFRP parts need to be cleaned of mold release agent residues and debris imparted to the surface during the molding process. A thorough cleaning and surface texturing of the part without damaging the fibers is crucial to achieve higher joint strength.

Painting of CFRP parts is also challenging due to low surface wettability and poor surface adhesion, both of which can be improved with laser processing. A thorough cleaning and texturing of the surface prior to painting improves wettability and hence adhesion of paint to the surface.

The commonly practiced CFRP surface cleaning and texturing techniques are the use of peel-plies and mechanical abrading (OR grit blasting). While the peel-ply technique can provide a reproducible roughness of the surface it requires lamination of peel-plies onto the surface prior to molding and hence adds manufacturing steps and cost. Repeatability of the peel-ply process is questionable since the top resin layer thickness after the peel-ply process tends to vary across the part surface. Also release agent residues are sometimes transferred from the peel-ply onto the part, hence affecting the joint strength.

The major disadvantages of mechanical abrading technique are low throughput speed and use of wet chemicals. Hence a subsequent rinsing and drying of the part, which adds manufacturing steps and cost, is necessary. Also the technique is commonly performed manually, making it very time consuming and difficult to implement for large CFRP parts. The technique also has high process variability and the risk of damaging fibers. The grit blasting technique also tends to damage fibers and leaves residue and dust on the part which requires subsequent cleaning and drying needing additional manufacturing steps.

To overcome limitations of peel-ply and mechanical abrading techniques, lasers have been considered as an effective tool for CFRP parts pre-treatment for cleaning and texturing the surface. Lasers are known to provide a dry, non-contact, precisely controlled high speed process. Research show that parts pre-treated using UV and near infrared (IR) lasers can achieve lap shear strength similar to that of an abraded parts [10]. However, the high absorption of UV laser radiation inside the matrix material compared to near IR lasers is advantageous for avoiding possible material damage by delamination. Also, the process window for UV lasers is wider compared to near IR lasers. Using the Quasar 355-60 UV laser, we have demonstrated an area cleaning and surface texturing rate of 18 m^2/hr without any visible damage to the fiber.

In a collaboration work with the Institute of joining and welding (TU Braunschweig), Germany we have conducted the standard DIN EN 1465 lap shear strength test of 2 mm thick aerospace grade unidirectional CFRP samples. At a pull speed of 5 mm/min using 150 μm thick AF 163 adhesive, manufactured by 3M Corporation, Quasar UV laser cleaned and textured parts showed about the same strength as mechanically abraded parts. Data also showed that untreated parts had lower strength then cleaned and textured parts. Also high percentage of undesirable adhesive failure modes were observed for untreated parts indicating very poor adhesion. The strength test was repeated after aging the samples for 1000 hours in a 70^0 C, 100% humidity chamber. The shear strength for all aged parts decreased as expected, due to degradation occurring in the adhesive. However, the advantage of cleaning and texturing of parts is evident from the data since the drop in shear strength of untreated parts is higher compared to cleaned and treated parts. The laser treated samples had the smallest decline in lap shear strength as shown in Figure 5 below.

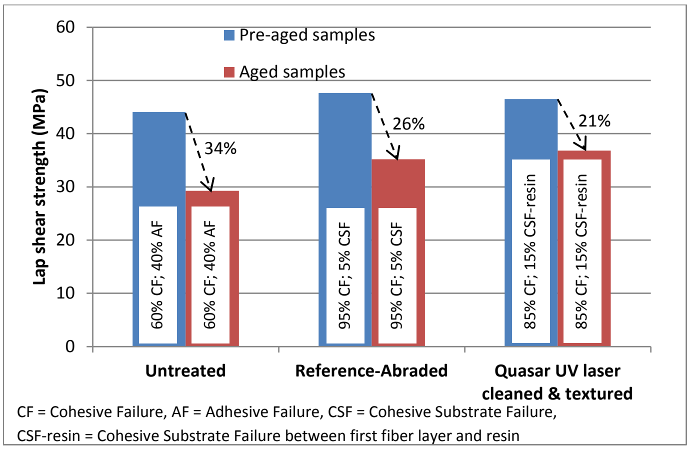


Figure 5: Lap shear strength test data for untreated, reference-abraded and Quasar UV laser cleaned and textured parts.

5 CONCLUSIONS

The wide spread use of CFRP materials across various industries requires fast, high quality and high yield machining processes to take full advantage of the benefits CFRP materials offer. The use of high power infrared and ultrashort pulse lasers for machining CFRP does not provide a good balance of processing speed and quality. We demonstrated that pulsed UV nanosecond lasers are a very promising tool for CFRP processing. With the >60 watts UV Quasar laser, the high power and programmable pulse width/shape result in both high speed and quality for CFRP processing, including cutting, drilling, surface texturing and cleaning. With this high power UV laser, we demonstrate that low HAZ without damaging the carbon fibers can be achieved with high cutting speeds. Also, UV laser cleaning and texturing of CFRP parts is shown to yield stronger joints. Further work is actively being pursued to extend to other configurations of processes and thicker materials and to expand the study of the effect of laser parameters on machining CFRP.

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