Application of Fiber Lasers for Cutting of CFRP Composites

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ABSTRACT

There is an increasing trend to use products manufactured from the Carbon Fiber Reinforced Plastics or Carbon Fiber Reinforced Polymer (CFRP) composites in the industry like aerospace, automotive, sports, medical, renewable energy etc. It is because of the lighter weight, higher strength, hence, higher strength-to-weight ratio of these materials, their higher corrosion resistance, higher fatigue resistance etc. Manufacturing of products from CFRP composites need precise machining, including cutting. Cutting of these materials is very difficult and inefficient with non-laser traditional techniques. Using continuous wave (cw) or pulsed fiber lasers solves many of these limitations of cutting CFRP composites. These processes have been optimized by many researchers for reducing the heat affected zones (HAZ) by optimizing the laser parameters like its power, pulse duration, feeding speed etc. Finally the environmental hazards of laser-based cutting of CFRP composites and the safety measures are also discussed in this paper.

Keywords: Laser cutting, CFRP composites, Carbon Fiber Reinforced Plastics, Polymers.

1. Introduction

A composite material can be defined as a mixture of two or more materials to produce the characteristics that are different from those of separate materials. Carbon Fiber Reinforced Polymer (or Plastic) Composites have great potential for the current and future industry due to their lighter weight, higher strength, higher strength-to-weight ratio, higher corrosion resistance, higher fatigue limit etc., among many characteristics. In competition with other materials as high-strength steel or light metals, the market forecast for carbon fiber reinforced materials predicts a continuous growth of around ten percent per year as it was achieved in the recent years. The industrial usage of carbon fiber reinforced plastic (CFRP) is steadily increasing, with more than 70,000 tons per year. Machining of this material (including cutting) for manufacturing of products is very difficult and inefficient with non-laser traditional techniques. Using continuous wave (cw) or pulsed fiber lasers solves many of these limitations of cutting CFRP composites, which are discussed in details in this paper.

1.1 Introduction to CFRP composites

Composite material is made from two or more constituent materials of different properties. In the composite one of the constituent is called the matrix and other constituent material is called reinforcement. The matrix helps in providing the final shape, protecting the reinforcement as well as distributing the stresses to the reinforcement, whereas reinforcement provides a composite the desired mechanical properties in preferred direction. Generally brittle and strong fibers are incorporated with ductile and soft polymeric matrix, and are called fiber reinforced plastics (FRP). The fibers generally used are glass, carbon or aramid. Glass, carbon, aramid and boron fibers are generally used as reinforcements in composite materials to increase their stiffness and strength. Due to the carbon fibers, Carbon Fiber Reinforced Polymer Composites, or CFRP Composites for short, is a term used to describe a fiber reinforced composite material that uses carbon fiber as the primary structural component. The letter 'P' in CFRP can also stand for "Plastic" instead of "Polymer." Carbon fibers are commonly produced from three organic fibers, such as rayon, polyacrylonitrile (PAN), and pitch. PAN is the most popular that is drawn into fibers and then stretched and thermally treated for sizing to increase their mechanical properties. CFRP parts have a high specific strength parallel to the composite layers, whereas the strength perpendicular to these layers is mainly determined by the matrix properties. Carbon fibers are nearly five-times stronger than steel, three times lighter, twice as stiff and have better yield strength. CFRP composites are lightweight, corrosion resistant, much stronger and stiffer as compared to glass fiber and even metals [1]. This makes them particularly interesting for numerous products as an alternative to traditional steel or other metals.

1.2 Applications of CFRP composites

Due to its high strength-to-weight ratios, corrosion resistance and low thermal expansion, CFRP composites have become attractive for use in many applications such as aerospace, automobile, marine, missile structure, medical and sports equipment components. In the aerospace field, CFRP composites are used in aero-engine fan blades, fuselage and wing construction. For example, more than 30% and 50%, of CFRP laminate have been used in Airbus A350 and Boeing B787 respectively. Also, about 25% of the F-22 fighter weight is CFRP. [2] The use of CFRP in space vehicles and automobiles ensures that weight reduction, and hence fuel consumption and efficiency are improved. An example of such applications can be found in the space telescope and BMW M6 roof panel. Furthermore, BMW used CFRP to construct the passenger compartment for its first mass production BMW i3 electrical car. For example, semi-structural parts such as roof, engine hood, car wings and door panels are promising automotive applications for such composites. The corrosion resistance and high strength-to-weight ratios of CFRP enable longer car's lifespan and lightweight car body than metal. In medical field, CFRP is used for hip-joint endprosthesis, whereas in sport fields, CFRP is used in tennis racquet, sailboats, bicycle frames and golf sticks. Further, CFRP material is also used advantageously in the manufacturing of blades in the wind energy industry.

The increase in the use of CFRP necessitates the need for the successful development of machining technologies, including cutting of this material in order to obtain better quality of finished products.

2. Cutting of CFRP by traditional techniques vis-à-vis lasers

Commonly used methods of cutting CFRP is by mechanical means that has found many problems including extensive tool wear, fiber pull-out and de-lamination. CFRP composites are more difficult to machine than conventional materials generally because they are heat sensitive and the carbon fibers are very abrasive. The inhomogeneity in the material properties and structures of CFRP composites makes their machining difficult by using mechanical, electrical discharge, and abrasive water jet machining. Abrasive water jet machining as an alternative processing technique yields good cut quality (no heat affected zones) with lower tool wear than mechanical processing. However, such techniques need to cope with the water treatment, acoustic noise hazards and abrasive slurry disposal. Some studies have shown that water jet (WJ) or abrasive water jet (AWJ) cutting technique is better in comparison to laser cutting process showing the capability of this technique. But the microbial growth like fungus on the cut surfaces after few days of storing is one of the major problems while machining with WJ/AWJ machining.

Lasers as non-contact tools have been widely applied for cutting materials. The application of laser cutting technology has a great potential because of its wearless and forceless performance. One challenge of laser processing of CFRP, however, is the extension of so called heat affected zone (HAZ) at cutting edge. These HAZ is a result of big difference between the decomposition temperatures of resign and fibre material, for example, the decomposition temperature of carbon fibre is about 3000 K and of epoxy resin, it is about 550 K. Machining of CFRP composites using lasers can thus be challenging due to inhomogeneity in the material properties and structures, which can lead to thermal damage such as charring, heat affected zones (HAZs), resin recession and de-lamination. It has been shown by some researchers [1] that the pulsed fiber lasers can improve the machining quality of CFRP compared to that with the continuous mode lasers. The process parameters that affect the width of HAZ in laser cutting of FRP composites are the cutting speed, gap between two cutting paths, and the assisting gas purging rate. The laser energy per unit traverse length and the resultant thermal conductivity due to fiber orientations are some of the dominant factors determining the area of impact of HAZ.

2.1 Fiber laser and its advantages

The active medium of a single mode fiber laser (to be discussed here) is a core of the fiber doped with a rare earth (erbium, ytterbium, neodymium) and is excited by a diode laser source. The laser cavity is made directly with an active fiber. The pump beam is launched longitudinally along the fiber length and guided by the core Two Bragg gratings reflect a certain incident wavelength of light while rejecting the other wavelengths. This laser beam has a high beam quality. A coil of ytterbium-doped multi-clad fiber with an emission wavelength of 1.07-1.08 µm make up the high power fiber lasers that are used widely for cutting applications. The wall plug efficiency of a ytterbium fiber laser is typically 20-30 %, and it needs less maintenance compared to other lasers because there is no need to replace flash lamps or diodes. A 1-kW fiber laser can be focused to a 50-µm spot size.

The use of ultrashort pulsed lasers (femtosecond and picosecond) improves the material processing quality as compared to long pulsed lasers because of its high precision machining and minimum thermal/mechanical damage. The reduction in beam/material interaction time using ultrashort lasers leads to higher quality machining by reducing the heat affected zone (HAZ). High energy femtosecond pulsed lasers can be generated via the chirped-pulse amplification (CPA) technique [3].

The main advantage of the fiber laser is that the quality of the beam is high and it has a lower sensitivity against laser-induced plasma. High beam quality results in high brightness, long depth of focus and long working distance when long focal length optics is used. Other benefits can be identified as: high power output, low-cost, flexibility in beam delivery, acceptable life time, multi-output potential, and beam shaping potential.

3. Fiber Laser Cutting of CFRP Composites

Laser cutting is a thermal process in which the efficiency of machining depends on thermal and physical properties of the material rather than its mechanical properties. In laser cutting, when a focused laser beam is incident upon the workpiece, part of the heat generated is absorbed by the material surface and then conducted to the workpiece. Depending on the power density, the absorbed energy heats and converts a portion of the processing zone into a molten, vaporizes or chemically degrades the material (in the case of resin matrix material) creating a narrow kerf width with a certain depth through the thickness of the workpiece.

(Kerf is the width of material that the process removes as it cuts through the piece of the material.) In the industrial applications, low kerf width is always preferred as a quality parameter of the machined workpiece. With the help of a coaxial gas jet or recoil pressure, the volume of evaporated or melted material is removed from the cutting zone.

In an experiment [4], the comparison of extension of HAZ and kerf width with rising feeding rate for Yb-doped fibre laser beam cutting of a CFRP laminate was demonstrated. Both HAZ and kerf width decreased significantly with rising feeding rate and a constant laser beam power of 1.5 kW. Minimal kerf width was typically about focal diameter of 98 µm while the realised kerf width averaged between 140 to 190 µm.

3.1 Laser fusion cutting

This process involves melting of the base material using laser heat energy. The molten material is then driven out of the machined kerf using high pressure inert gas (mainly nitrogen, helium or argon). During the laser fusion cutting, the laser beam only heats up the material above the molten temperature and the melt ejection is done by the assisting gas jet. The gas also shields the cut zone and protects the laser optics. However, the formation of striations on the cut surface and dross at the lower cut edge are the major drawbacks of the laser fusion cutting (Dross means the scum or unwanted material that forms on the surface of molten metal). Hence, striations and dross-free-cutting is the main challenge in this technique.

3.2 Laser reactive gas fusion cutting

Laser reactive gas fusion cutting is also known as laser oxygen cutting. In this process the inert gases are replaced with a reactive gas such as oxygen or a mixture containing oxygen. Besides ejecting the melted material, the oxygen gas also reacts with the melted material, through an exothermic reaction, which enhances the cutting process by providing additional heat inputs to the cutting zone allowing for higher cutting speeds than laser fusion cutting with inert gases only [33, 76, 80]. A mixture of oxygen with nitrogen gas was found to improve the machining quality in laser cutting of CFRPs [5].

3.3 Laser vaporization cutting

Laser vaporization cutting involves heating the material to the vaporization temperature by a high intensity (over 106 W/mm^2) focused laser beam. The material is vaporized and ejected with molten material by the help of the assist gas jet. Generally a pulsed laser combined with a coaxial jet of inert gas is used with this process. In short pulse lasers, most of the material is vaporized due to the high peak power. Less melting during the process helps to achieve high edge equality. Some polymers, wood and polymer composites are cut through vaporization cutting [6].

4. More about Heat Affected Zone (HAZ) during Laser Cutting

The heat flow, H is the rate of energy transfer, $\Delta Q/\Delta t$, through the material. This is proportional to the cross-sectional area A and to the temperature gradient $\Delta T/L$. Here A is the 2-dimensional “width” of the path connecting the hot part of the object to the cold part, and L is the length of material the heat passes through.

$$H = \frac{\Delta Q}{\Delta t} = K\,A\,\frac{\Delta T}{L} \qquad (1)$$

But thermal conductivity is not the only factor that influences the heat flow. The rate of change of temperature also depends on the specific heat c of the material. In fact, the heating rate is inversely proportional to the specific heat per unit volume, which is equal to ρc, where ρ is the material density. The important factor for heat flow is k (= K/ρc). It is known by the term "thermal diffusivity," to recognize that it represents the diffusion coefficient for heat.

The HAZ during laser processing of materials can be estimated from the heat penetration depth (D):

$$D = (4\,k\,\tau)^{1/2} \qquad (2)$$

Where k is the thermal diffusivity (cm^2 /s) and τ is the laser pulse duration (sec).

Among all the different cutting quality parameters discussed above, HAZ is unavoidable and is a critical factor in evaluating the laser cutting quality of CFRP composites. Thus, the possibility of reducing/eliminating HAZ is an important challenge.

Laser machining of CFRP composite materials is very challenging due to the large differences in physical and thermal properties of the CFRP constituents. The best quality of FRP laser machining can be achieved when the thermal properties of the reinforcing fibers and polymer matrices are close to each other and reacts to the heat in a similar manner as in case of aramid fiber reinforced polyester composites. The amount of damage to the matrix material during laser cutting is mainly dependent on the absorbed energy, which does not contribute to the desired material removal. This excess energy and the different thermal properties of the reinforcing fibers and the thermoplastic matrix material, especially their different deterioration temperatures and thermal conductivities, can result in heat affected zones (HAZ).

In CFRP composites, the thermal conductivity, thermal diffusivity and heat of vaporization of the polymer are lower compared to the carbon fibers. Hence, during laser machining of CFRP, the matrix is affected by the laser heat before the carbon fiber which needs higher temperature to vaporize. Furthermore, the large amount of energy presented in the laser cutting zone is conducted away due to the high thermal conductivity of carbon fiber. Also the difference in thermal conductivities between the fibers and polymer matrix makes it difficult to obtain uniform and high quality machining of CFRP using a laser. Consequently, laser processing of these materials often leads to an extended HAZ. Minimising or eliminating HAZ in the polymer matrix in laser processing of CFRP is considered as the major obstacle for its wide industrial applications.

4.1 Application of ultrashort pulse lasers to minimize HAZ

Since the HAZ is influenced by the laser material interaction time, a short-pulsed laser is an option to reduce the laser-material interaction time and offers improvements in cutting quality due to the cooling between pulses. Therefore, the use of ultra-short laser pulsed sources such as femtosecond lasers and picosecond lasers allow the release of high pulse energy in a very short time. The laser beam directly evaporates the materials and leaves little time for the heat to propagate to the adjacent substrate and hence limiting the HAZ extension and improving the laser machining quality for processing CFRP. With ultrashort-pulsed fiber lasers of 1-kW power at around 1-µm wavelength and a fast beam-deflecting device to avoid excessive pulse overlapping, the best edge quality in CFRP laser cutting is possible if high scan speeds in the m/s range and appropriate cooling breaks are applied.

Emmelmann et al. [7] analysed the extension of HAZ at the cavity edge during laser ablation of CFRP laminate by machining quadratic cavities into a CFRP laminate using two different lasers; a 1 ns fibre laser with a wavelength of 532 nm and a 2 ps solid state laser with a wavelength of 1064 nm. They concluded that pulse duration has a significant effect on the material processing quality with shorter pulses giving much reduced HAZ.

Finger et al. [8] investigated the processing of a 2 mm thick CFRP composite sample using a picosecond pulsed laser with an average power of up to 80 W. They also evaluated the influence of the average power, scanning speed and repetition rates on the ablation rates and the width of HAZ. They showed that picosecond laser processing of CFRP with a HAZ less than 5 μm and an ablation rate of 100 mm3/min could be obtained. The use of a high average powered picosecond laser often involves high repetition rates, which can damage the processed material by excessive heat accumulation.

Weber et al. [9] used a ps laser at a wavelength of 515 nm with pulse duration of 8 ps, a maximum average power of 23 W and a repetition rate of 800 kHz to investigate the effect of heat accumulation on cut quality of CFRP. They concluded that at high repletion rates, short pulse lasers with very high scanning speed are required.

Freitag et al. [10] used an ultrafast laser system with an average power of 1.1 kW, 8 ps pulse duration and 300 kHz repetition rate to investigate the effect of heat accumulation during picosecond laser processing of CFRP. They showed that the heat accumulation effect could be reduced by decreasing pulse overlaps using higher feed rates.

Multi-kW single-mode fiber lasers have been shown to provide the necessary power and power density to cut consolidated FRP in a cutting speed range of meters per minute. A multipass processing strategy with well-adjusted scan speed and interval times between the scans has been demonstrated [11] to achieve high-quality cut edges with acceptable productivity. In the case described here, the available scan field for processing the demonstrator part was 200 × 200 mm². The contour that had to be trimmed was an 800 mm line at both long sides of the part. Thus, superposed axis of the scanner and a robot, moving the scan field over the demonstrator part, were applied to cover the whole cut length. During the continuous movement of the robot the scanner processed repeatedly a section of the cut path in the scan field.

Hirsch et al [12] used a single mode fiber laser for cutting and investigated the resulting mechanical properties of continuous fiber-reinforced polyamide 6 composites (TPC). It was found that at the same scanning speed, the single mode fiber laser cutting of glass fiber-reinforced TPCs required a significantly higher number of cutting cycles which led to a bigger average HAZ as compared to carbon fiber-reinforced TPCs. Additionally, the formation of the HAZ was found to be dependent on the laminate structure and break time, with a reduced HAZ when laser cutting perpendicular to the fiber axis and a higher break time was applied. It was found that the occurring HAZ only slightly influenced the mechanical performance of carbon fiber composites.

4.2 Continuous Wave (CW) Fiber lasers for cutting CFRP composites

In another investigation [13], a 400 W fiber laser source was deployed to cut CFRP composite sheets, and the surface integrity of the cut surfaces was evaluated. Kerf width, HAZ, and percentage of taper formation in the cutting plane had been considered as the surface integrity parameters. The optimization of process parameters was carried out to find out the suitable combination of input parameters for improvement of surface integrity. The cutting was performed by using a Fiber Laser of 400 W with a fundamental wavelength of 1070 nm and with continuous mode of operation. A fine laser cutting head was mounted to the Z-axis CNC stage. The work holding fixture was mounted over the X-Y stages. A controller was used for controlling the motion of all the three stages. The maximum traversed speed of all the stages was 5000 mm/min. A fixture was fabricated to hold the CFRP sheet that moves under the cutting head during the cutting operation. The cutting head was facilitated with the gas purging facility through which the assisting gas (CO_2) was purged to reduce the burning of the work material due to the presence of atmospheric oxygen. The optimum values of process parameters corresponding to best-cut surface quality found were: laser power 260 W, cutting speed 4500 mm per min, and assistance gas flow rate 14.23 l/min. Kerf width, taper percentage, and width of HAZ were found to be 163.7 μm, 5.75%, and 573.28 μm, respectively, at an optimum level of process parameters.

Niino et al [14] reported the laser-induced damage during laser cutting of CFRPs using a continuous-wave (CW) kW-class fiber laser (λ = 1,084 nm). Laser cutting of CFRP was performed by multi-pass irradiation with a continuous-wave fiber IR laser (multi-mode laser, average power: 3.3 kW). The damaged sidewall of the trench in the samples was analyzed by microscopic X-ray computed tomography. Low-speed laser scanning with a galvanometer scanner significantly damaged the sidewall surface and created a wide heat-affected zone. As the thickness of the damaged area was correlated with the scanning speed of the laser beam, the damaged region length was analyzed using the heat penetration depth equation. The authors concluded that a systematic analysis of laser beam scanning speed resulted in a good correlation between the laser irradiation time and the extent of damage near the sidewall.

Herzog et al [15] have shown that by increasing laser power from 1 kW to 4 kW, the cutting speed could be increased from 5 m/min to approx. 22 m/min, and the dimension of the HAZ decreased from approx. 500 μm to 250 μm. Increasing the power of fiber laser further to 16 kW could yield higher cutting velocities of up to 80 m/min, and the HAZ was further reduced to values of approx. 180 μm. Using 30.5 kW of laser power focused down to a spot of 244 μm in diameter, it was possible to cut a 1.4 mm thick CFRP laminate in a one-pass strategy at 1.2m/s and with a mean HAZ of 139 μm. With a multi-pass strategy, finding its optimum in a range between 12–16 passes, the HAZ was further reduced down to 78 μm.

5. Environmental hazards of cutting of CFRP composites by lasers

While we have described above the advantages of cutting of CFRP composites with lasers, a word of caution needs to be mentioned before we jump to the conclusion of adopting laser-based cutting techniques as panacea for every problem. The laser energy input causes a considerable emission of fumes and organic gases, influenced by various material and process parameters. The composition of these process emissions is complex, and they may contain a significant amount of toxic or even carcinogenic components [16]. Furthermore, a lot of ultrafine particles, having the potential to be incorporated into the pulmonary alveoli, may be generated. So far, there is only little detailed quantitative information on the release of particulate and gaseous emissions during laser cutting and ablation of CFRP, as well as regarding the requirements for adequate measures concerning occupational safety and environmental protection. For instance, it is not known if the fumes contain fibrous particles which may behave similar to asbestos fibers in the lung tissue due to their geometry. Therefore the values of environmental exposure limits have to be met by adequate measures, starting from technical measures to reduce hazardous substances, to organizational measures such as preventing access to the working area, if technical measures are not sufficient, and finally to personal protective equipment for employees who have to stay in the working area in spite of hazardous substances.

The experiments conducted by Waltera et al [16] have shown that relevant amounts of volatile organic compounds (VOCs) and carbon monoxide as well as of spherical and fibrous particles are emitted during laser cutting of different CFRP materials, namely carbon fiber composites with thermosetting epoxy and with thermoplastic PPS matrix, respectively. Obviously, choosing an optimized cutting strategy for these materials, that is, multipass cutting with additional breaks to allow for sufficiently long intermediate cooling-down phases of the material, helps not only to improve the cutting qualities considerably, but also to reduce the hazardous emissions. Filtering the exhaust air with a surface filter to remove the aerosols, and then with an activated charcoal filter to absorb the VOCs and the carbon monoxide, ensures protection of the environment adequately. These methods of cleaning the exhaust air are well-established. Especially in case of CFRP, catalytic cleaning appears to be a promising alternative, as all components of the composite materials can potentially be transformed to less hazardous substances such as CO2 and H2O and thus no hazardous residuals have to be dealt with.

6. Conclusion

In this paper, we have highlighted the importance of the products manufactured from the CFRP composites in the industry like aerospace, automotive, sports, medical, renewable energy etc. The increasing demand of these composites is because of their lighter weight, higher strength, hence, higher strength-to-weight ratio, their higher corrosion resistance, higher fatigue resistance etc. Manufacturing of products from CFRP composites need precise machining, including cutting. Cutting of these materials is very difficult and inefficient with non-laser traditional techniques. It has been extensively discussed here that using continuous wave (cw) or pulsed fiber lasers solves many of these limitations of cutting CFRP composites. Laser-cutting processes have been optimized by many researchers and discussed in this paper for reducing the heat affected zones (HAZ) by optimizing the laser parameters like its power, pulse duration, feeding speed etc. Finally the environmental hazards of laser-based cutting of CFRP composites and the safety measures have also been discussed in this paper.

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