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Laser cutting of Carbon Fiber Composite materials

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Abstract

Carbon fiber reinforced plastic (CFRP) composites are materials widely used for many applications due to its high strength, specific stiffness and inherent low density. CFRP composites are easily tailored to a particular application, which made them very attractive for structural applications, especially for aeronautics.
The potential of such composites to be cut by a high quality CO_2 laser was investigated in this work. A 3.5 kW CO_2 slab laser was used to cut CFRP plates with a thickness of 3 mm. The influence on the cut quality of different processing parameters such as pulse frequency, pulse energy, duty cycle, type and pressure of the assist gas were studied. The quality of the cuts was evaluated in terms of kerf width, perpendicularity of cut kerf, delaminating degree, and extension of the heat affected zone (HAZ). The process was optimized and selected processing parameters values were used to obtain good quality cuts.

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Keywords: CFRP, laser cutting, assist gas, CO_2 laser, heat affected zone

1. Introduction

Carbon-fiber-reinforced polymers (CFRP) are particularly attractive materials for structural applications due to their high specific strength, and stiffness, combined with a low density. These composites are manufactured combining two phases, which remain separate and distinct on a macroscopic level, namely a polymeric matrix, and a fiber network dispersed into it [1]. This inhomogeneous structure is essential to achieve their extraordinary structural properties; however, it makes more difficult the possibility to produce sound cuts by thermal processes such as in laser cutting. The large differences between the physical properties of polymer matrix and the carbon fibers greatly influence the process of laser cutting. On one hand, the energy required to melt or vaporize the fibers is, in general, higher to that required to melt or vaporize the polymeric matrix. On the other hand, the thermal conductivity of the fibers is much higher than that of the polymeric matrix. Therefore, the heat generated during laser cutting will degrade a large extension of the polymeric matrix [2]. However, the possibility to cut these materials by laser is very attractive from an industrial point of view. The possible application of this manufacturing technique would afford substantial costs associated to the processing of these materials.

Many researchers have studied the potential application of laser cutting in CFRP composites [3-8]. Pioneering studies of Tagliaferri et al. [3] demonstrated the large difficulty to obtain sound cuts in CFRP's as compared to glass (GFRP) or aramid

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(AFRP) fiber composites, due to the larger difference in the thermal properties of the matrix and the fibers. Caprino and Tagliafferi [4] developed a criterion to classify the quality of the cuts in three ranges. Cenna et al. [5] reviewed the problems related to the laser cutting of composites, and discussed the relevant aspects related to the process. This work suggests different approaches to reduce the heat-affected zone (HAZ) and improve the cut quality. Herzog et al. [6] studied the influence of the laser wavelength, during laser cutting of CFRP specimens 1.5 mm in thickness, using a pulsed Nd:YAG laser, a disk laser and a CO_2 laser. They evaluated also the influence of the processing conditions on the HAZ extension and on the static strength. The HAZ extension was smaller using the Nd:YAG laser. Herzog et al. [7] used a multipass strategy in order to reduce the HAZ. CFRP laminates with 1.5 mm in thickness were processed using a 30 kW fiber laser. 12–16 passes with scanning speeds around 1.5 m/s were required to obtain a significant reduction in the HAZ. However, this multipass strategy requires more passes for thicker samples [8]; then, this strategy is not efficient for cutting thick workpieces.

In this work, it is determined the influence of the processing parameters during CO_2 laser cutting of a CFRP composite to determine the optimum processing conditions required to minimize the HAZ extension. The influence of the pulse frequency and energy, duty cycle, type of supply, and pressure of the assist gas on the cut quality was evaluated. Cut quality is based on the visual inspection of the cut surfaces, measurement of the kerf width in the entry and exit side of the cut, taper angle, HAZ extension.

2. Material and methods

The base material used in this study was a CFRP composite sheet, 3 mm thick. The main characteristics of this CFRP composite and its component physical properties are listed in Tables 1 and 2, respectively. The reinforcing material is a T300-3000 carbon fiber manufactured by TORAY. The matrix is an epoxy resin F-263 manufactured by HEXCEL. The weave pattern of the composite is a plain weave.

All experiments were performed by means of a Rofin-Sinar CO_2 slab laser (model DC035). This laser source delivers a maximum output power of 3.5 kW in CW mode at a wavelength of 10.6 µm with a high quality beam (beam quality factor $K \geqslant 0.9$) due to the excellent mode structure provided by the slab technology of the laser cavity. The laser beam was focalized with a ZnSe lens (focal length 127 mm) onto the surface of the workpiece.

In order to determine the influence of the laser pulse mode on the process, tests were conducted in continuous wave (CW) mode and in pulsed mode. In CW-mode, the laser power varied from 200–2000 W, and the cutting speed from 200–4000 mm/min. In pulsed mode, the average laser power ranged from 300–3000 W, the cutting speed from 200–4000 mm/min, and the pulse frequency and duty cycle in the ranges 10-4000 Hz, and 20-100 % respectively.

Finally, we have determined the influence of the assist gas injection system on the cutting process. Tests were performed using a subsonic and a supersonic assist gas jet in order to compare results. A cutting head with a subsonic (conical coaxial) nozzle with an exit diameter of the assist gas jet of 2 mm was employed in the subsonic tests, with a stand-off value of 1.5 mm. On the other side, the supersonic experiments were performed using a cutting head with an off-axis supersonic nozzle. The details of the supersonic nozzle are described elsewhere (see, for example Ref. [9]). The assist gas jet used in all the experiments was Argon. The assist gas pressure was 4 bar in the conical coaxial cutting head (except in those tests carried out in order to study the possible influence of the assist gas pressure), and 8 bar in the supersonic cutting head.

Table 1. Main properties of carbon fiber composite.

Geometry	Thickness (mm)	Reinforcing material	Matrix	Wave pattern	Fiber volume	Void volume
Flat	3	T300-3000 carbon fiber (TORAY)	epoxy resin F-263 (HEXCEL)	plane wave	0.57	0.02

Table 2. Physical properties of the carbon fiber composite.

	Density (g/cm^3)	Conductivity (W/cm°C) 10^{-2}	Specific Heat (J/g°C)	Diffusivity (cm^2/s)	Vaporization Temp. (°C)	Vaporization Heat (J/g)
Resin	1.25	0.2	1.2	1.3	500	1000
Carbon Fiber	1.85	50	0.71	380	3300	43000

After cutting experiments, selected samples were sectioned perpendicularly to the cut edge with a precision cut-off machine (Struers Minitom), and subsequently embedded in epoxy resin, and finally grinded with SiC paper and polished by diamond paste up to 1 µm finishing. These specimens were inspected in frontal and cross-sectional direction to the cut edge using an optical stereoscopic microscope (Nikon SMZ-10A) with a photographic system in order to record and store the images. Furthermore, both the cut edge, and its cross-section were studied after the laser cutting process through scanning electron microscopy (SEM). Samples obtained from each specimen were covered with a thin gold layer and examined in a Philips XL-30 SEM.

In order to analyze the cutting process, quality characteristics evaluated in this work were the kerf width, the slope of the cut edge (also called taper angle), and the width of the HAZ.