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Effect of laser cleaning in Laser Assisted Joining of CFRP and PC sheets

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ABSTRACT

The present paper investigates the influence of laser cleaning of Carbon Fibre Reinforced Plastic (CFRP) surface when joining CFRP to Polycarbonate (PC) sheet by means of laser assisted Joining.

Experimental tests were conducted to perform polycarbonate-CFRP (with epoxy matrix) joints. The laser cleaning treatment was carried out on CFRP laminate adopting a 30 W Q-switched Yb:YAG fibre laser. Laser assisted joining was performed adopting a continuous wave 200 W diode laser. Untreated samples were adopted as reference. Morphological analysis and single lap shear tests were conducted to characterize the joints. Infrared thermography (IRT) was carried out to determine the temperature distribution and variation during the joining process. ANalysis Of VAriance was applied to investigate the effect of the process parameters, (laser power, energy, and treatment) on the extension of the bonded area and the mechanical properties. The results show that laser pre-treatment enables a significant increase of the joint strength which is, under the optimal conditions, more than double than the reference samples: However, considering the apparent shear strength, the laser pre-treatment does not produce a significant advantage, as it mainly resulted in the enlargement of the bonded area.

1. Introduction

The growing demand of light-weight structures, especially in transport, results in wider employment of hybrid structures made of different materials. In this context, the employment of multi-material assemblies represents a possible solution; coupling materials with different physical and mechanical behaviours can offer different opportunities. For example, in the case of Carbon Fibre Reinforced plastics CFRP coupled with polycarbonate (PC), it is possible to obtain hybrid structures, characterized by high strength and toughness, with the presence, if necessary, of transparent areas, for inspection or aesthetical reasons. On the other hand, as PC shows good impact resistance, it can be adopted either as matrix for Carbon Fibre Reinforced Thermoplastics (CFRTP), as adopted in Ref. [1], or as core between two thin plies of carbon cross textile fibre/epoxy (CFRP/PC/CFRP) [2].

The main concern of multi-material assemblies is the adoption of a suitable joining process. Mechanical joining processes (such as riveting or bolting) [2] are often adopted for this purpose. However, the stress concentration and the long working time, due to the drilling operations, represent great limitation to their application. In recent years, fast mechanical joining methods, which do not require pre-drilled holes, were developed, such as Self-Pierce Riveting (SPR) and Mechanical Clinching (MC). Owing to their simplicity, robustness, low cost, and high productivity, many studies were conducted to adapt these processes to hybrid metal–polymer [3,4] and metal–Fibre Reinforced Plastics (FRP) [5–8] joints. However, these processes still suffer some drawbacks; e.g. high stress concentration (due to the spot joints) and the requirement of access from both sides of the joint. In addition, when continuous fibres are adopted as reinforcement, delamination is present near the joint [7,9]. Finally, these processes can be employed only when the material placed on the punch side has high strength and shows certain plasticity.

Besides mechanical joining processes, adhesive bonding [10] and welding [11] are also widely used. Adhesive bonding enables good stress distribution, good fatigue life, corrosion resistance, and high strength-to-weight ratio as compared to mechanically fastened joints. In addition, it does not cause stress concentration or fibres interruption. Despite these advantages, adhesive bonding shows some drawbacks and special requirements, including: substrate preparation, long processing time (due to preparation of substrate and curing time), specialized workers and involves high environmental impact, due to emission of volatile organic compounds as well as the employment of solvents used for substrates preparation [12]. In addition, adhesive bonding introduces a third material (the adhesive) during the process [13] and

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bonding thermoplastic matrix composites requires special attention given the low chemical affinity of this matrix with the structural adhesives.

In order to overcome the aforementioned limitations, in last years, new joining processes, such as Friction Lap Welding (FLW), friction spot welding, and friction based stacking, were developed and studied. For example, FLW was adopted to joint metals to thermoplastics [14,15] or CFRP to aluminium [16,17]. Friction Assisted Joining was employed to join thermoplastic polymers [18,19], metals with thermoplastic polymers [20,21] and reinforced thermoplastic polymers [17,22–26]. Moreover, it was also adopted to joint metals with FRP with long fibres [22]. On the other hand, these processes enable obtaining joints with low quality finishing and they require very stiff clamping systems, due to high loads involved during the processes.

A valid alternative to the aforementioned joining processes are Laser Transmission Welding (LTW) and Laser-Assisted Joining (LAJ) [27] to weld thermoplastics and to join hybrid metal-plastic structures, respectively. During LTW and LAJ processes, the laser beam heats and melts the plastic component and promotes the adhesion (both mechanical and chemical). The substrates interface can be heated either by transmission of the radiation through the plastic, or by means of conduction throughout a heated metal. LAJ process is characterized by several advantages as compared to adhesive bonding, e.g. fast joining (no curing time), localized heating, no vibration, low residual stresses [28] and no employment of further components (i.e. the adhesive). During LTW and LAJ the parts need to be pressed together to reduce the gap and allow the adhesion [29]. However, fine calibration of the laser processing parameters (e.g. power, scanning speed, stand-off-distance, clamping pressure) is required. Indeed, previous studies indicate that these parameters influence the temperature distribution inside the bonded area [30], the residual stress [31], the presence of contact between the materials, the polymer crystallinity [32,33] and, hence, the bond quality and strength.

Recently, LTW was adopted to weld fibre-reinforced thermoplastics [34,35], like Glass Fibre Reinforced Polyamide (GFR-PA66) to PC, reaching a shear strength of 4 MPa [36]. To estimate the temperature distribution inside the bonded area and consequently to optimize the weld performance, LTW of composites requires accurate modelling of the interaction of the laser beam with semi-transparent composites [37]. However, when reinforced plastics are welded, high care should be paid to the fibres orientation. Indeed, carbon fibres have great thermal conductivity compared to the matrix material. Consequently, the heat is conducted along the fibres and the weld seam geometry is affected by the local orientation of the fibres [38].

So far, Laser Assisted Joining processes have been employed to weld thermoplastics [39–43], fibre reinforced thermoplastics [34–37] including CFRP composites [44–46] and different metals: PET-AISI304 [27], PET-titanium [47–51], PMMA-AISI304 [52,53], Polytetrafluoroethylene (PTFE)-titanium [54], PET-aluminium [55], ABS-zinc-coated steel [56], PC-AISI304 [57] as well as to join fibre-reinforced thermoplastics (PC, PA66, PE) [35,36,45].

In a previous paper [58], the LAJ of thermoplastics sheet and composite with thermosetting matrix was reported for the first time. In that work, the process was conducted without prior removing the layer of epoxy that covered the irradiated carbon fibres. Thus, the main mechanisms developed during the laser processing were determined: heating of the carbon fibres, vaporization of the covering layer of epoxy, heating the overlying thermoplastic material and adhesion between the fibres and the thermoplastic material. Different phenomena were involved in the process that limited the strength of the joints, including: production of fumes (of both the epoxy and polycarbonate materials since the high temperatures involved), thermal degradation of the polycarbonate with formation of entrapped fumes at the interface and bubbles, which reduced the effective adhesion area, degradation of the epoxy layer underlying the layer of exposed carbon fibres. These issues were found under all processing conditions. On the other hand, when low energies were adopted, poor epoxy was removed from the interface layer. This affected the joint strength as it reduced the adhesion area between the PC and the carbon fibres. Generally, in order to achieve the formation of the joint, the processing conditions should lead to the removal of the epoxy layer. To this end, a temperature of at least 400 °C should be reached. Such temperature is very close to that of degradation of the PC material (540 °C).

The present study deals, for the first time, on the effect of laser pre-treatment on the joint strength of PC sheet to CFRP laminate, obtained by Laser Assisted Joining. To this end, laser joining at different process conditions was performed on autoclave cured CFRP laminate and PC sheets, with and without a laser cleaning pre-treatment of the CFRP surface. The laser pre-treatment was carried out adopting a 30 W Q-switched Yb:YAG fiber laser; while the joints were performed adopting a 200 W diode laser.

After joints production, mechanical tests were carried out; ultimate tensile strength and apparent shear strength were measured. Moreover, fracture surfaces analysis was performed. Infrared thermography (IRT) was also performed in order to understand the interaction phenomena occurring during the laser joining. ANalysis Of VAriance was applied to study the influence of the process parameters (laser power, energy, and treatment), on the bonded area extension and the mechanical properties.

2. Materials and methods

2.1. Materials

Polycarbonate (PC) sheets, 2.0 mm in thickness, supplied by Bayer, were coupled to CFRP laminates with thickness of 1.5 mm. The CFRP laminate was manufactured by means of hot pressing for 2 h at 130 °C and 5 MPa, as suggested by the resin supplier. Plain weave (SK Chemicals, UGN200) carbon fibre prepegs (0/90°, 50% in the warp and weft directions, MRC Pyrofil, TR30S) and a thermosetting epoxy resin (bisphenol-A type epoxy + phenol novolac type epoxy) were used for the production of the CFRP laminate [7]. The thermal characteristics of the materials are summarized in Table 1.

2.2. CFRP laser cleaning

Laser cleaning pre-treatment of the CFRP laminate (removal of the covering epoxy layer) was performed by means of a 30 W Q-switched Yb:YAG fibre laser (YLP-RA 30-1-50-20-20 by IPG), working at the fundamental wavelength of 1064 nm. In this laser system, the laser beam is moved by two galvanometric mirrors, placed into the scanner head, and, then, focused by a “flat field lens” of 160 mm in focal length. Thus, the resulting beam spot diameter is about 80 µm. In Table 2 the laser system characteristics are summarized. In order to treat the entire surface to be joined, more parallel lines, spaced of fixed quantities (called hatch distance, Hd), were performed, according to the procedures described in Refs. [62–64] and the schematic shown in Fig. 1. During the cleaning treatment the following parameters were adopted: hatch distance of 40 µm, beam speed of 2000 mm/s, average power of 30 W, pulse frequency of 30 kHz and pulse duration of 50 ns. Under these conditions the pulse power resulted of 20 kW and the pulse energy of 1 mJ. These values were selected on the basis of previous experiences

Table 1
Characteristic temperatures of polycarbonate and epoxy resin.

Material	Glass Transition Temperature, Tg [°C]	Melting temperature, Tm [°C]	Degradation temperature, Td [°C]
PC	154 [59]	230	540 [60]
Epoxy	165	–	450 [61]