Optics and Laser Technology 103 (2018) 170–176

Contents lists available at ScienceDirect

Optics and Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Full length article

CFRTP and stainless steel laser joining: Thermal defects analysis and joining parameters optimization

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ARTICLE INFO

Article history:
Received 11 September 2017
Received in revised form 3 November 2017
Accepted 5 January 2018

Keywords:
Laser joining
CFRTP
Stainless steel
Joint strength
Thermal defects

ABSTRACT

Experiments with different joining parameters were carried out on fiber laser welding system to explore the mechanism of CFRTP/stainless steel joining and the influence of the parameters on the joining quality. The thermal defect and the microstructure of the joint was tested by SEM, EDS. The joint strength and the thermal defect zone width was measured by the tensile tester and the laser confocal microscope, respectively. The influence of parameters such as the laser power, the joining speed and the clamper pressure on the stainless steel surface thermal defect and the joint strength was analyzed. The result showed that the thermal defect on the stainless steel surface would change metal's mechanical properties and reduce its service life. A chemical bonding was found between the CFRTP and the stainless steel besides the physical bonding and the mechanical bonding. The highest shear stress was obtained as the laser power, the joining speed and the clamper pressure is 280 W, 4 mm/s and 0.15 MPa, respectively.

1. Introduction

Carbon fiber reinforced thermal polymer (CFRTP) is one of the most important materials for structural applications, particularly in aviation industries owing to its high strength to weight ratio. In most real-life applications, CFRTP requires joining with metal frames to form complete structures, which play an important role in hybrid design. Most common joining methods between the CFRTP and metals include the mechanical joining, the adhesive bonding and the thermal joining [1]. The mechanical joining technology has advantages of high joint strength and long working time, but it has some drawbacks such as stress concentration and fiber damage [2]. The adhesive bonding technology has a better stress distribution, good fatigue life, corrosion resistance and high-to-weight ratio, however it has some drawbacks such as long curing time and high environmental impact. The thermal joining method has a better environmental adaptability compared with the adhesion bonding method, and has a more uniform stress distribution compared with the mechanical joining. Thermal joining methods includes the friction welding [3,4], the laser transmission welding [5,6] and the laser direct welding, etc. Compared with another two methods, the laser direct laser joining has some advantages such as low thermal effect, non-contacting, high-efficiency, suitable for opaque CFRTP, etc. Lots of investigations have been carried out on the CFRTP-metals laser direct joining in recent years.

Katayama and Miyashita [7,8] joined the PET and the stainless steel with the laser direct joining method. The mechanical bonding and the chemical bonding was found in the CFRTP/stainless steel joining interface, and lots of bubbles were observed, which would reduce the joint strength. Georgiev [9] used IR laser to join the PET and titanium alloy, and a Ti—F chemical bond was observed by XPS in the interface. By electroplating a Cr layer on the mild steel surface, and join it with CFRTP using fiber lasers, a Cr—O—PA6T bond was found in the joint interface, which improve the bonding strength greatly [10,11]. Some microgrooves were machined in the metal surface to improve the joint strength by Roesner [12], and then join the glass fiber reinforced thermal polymer (PA66GF30) with it using laser direct joining method. The joint strength was improved to 24 MPa. Researches on joining the CFRTP with stainless steel, aluminum alloy and galvanized steel were carried out by Kwang-Woon Jun [13–15], the influence of the joining parameter on the joint quality were analyzed. A. Heckert [16] found that the metal surface roughness, the fiber length and the polymer content of the CFRTP has effect on the joining shear stress. Lambiase et al. [17,18] applied laser-assisted direct joining method in joining the 304 stainless steel/polycarbonate and CFRTP/ polycarbonate, the main process conditions (laser power and scanning speed) influence the direct-bonds quality, dimensions and

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https://doi.org/10.1016/j.optlastec.2018.01.023
0030-3992/

presence of defect was investigated. It was found that the mechanical strength of the welds was highly affected by the Linear Energy Density (LE): low values of LE resulted in poor adhesion of the polycarbonate through the carbon fibres, which led to poor mechanical fastening and adhesion. On the other hand, processing conditions leading to excessive values of LE resulted in considerable damage of the composite matrix and formation of bubbles on the PC substrate, which produced a dramatic reduction of the mechanical behaviour of the welds. The finite element model of PMMA/stainless steel laser direct joining was established by Hussein et al. [19], and the simulated temperature distribution was compared with the thermal testing result. The result showed that the FEM model could predict the temperature exactly distribution in the joining process.

As mentioned above, most of the previous works focused on the CFRTP and stainless steel joint interface analysis, such as the microstructure and defects around the joint, the bonding mode of CFRTP/metal joint, the effect of the parameters on the joint strength, etc. However, few works investigated the thermal defect zone on the metal's surface, which affects the joint service life greatly and plays an important role on evaluating the joint quality. Experiments of joining the PPS-matrix CFRTP and the stainless steel were carried out in the present study, and the stainless steel surface thermal defect zone and the joining mechanism was analyzed by observing the microstructure through SEM and EDS. The influence of the joining parameter on the thermal defect zone and the joint strength was also investigated detailed.

2. Experimental procedure

The laser direct joining technology was applied to join the CFRTP and the stainless steel in this work. A 150 μm thickness PPS sheet was added between the CFRTP and the stainless steel to increase the melting PPS amount and to improve the joint strength. The joining principle is shown in Fig. 1. The laser energy is absorbed by the stainless steel as the laser-beam irradiates on it. The generated heat transfers into the CFRTP-stainless steel interface to melt the resin matrix. The added PPS sheet and the first layer PPS of the CFRTP melts. The melted PPS flows and diffuses in the interface under the clamper pressure. And a CFRTP-PPS-stainless steel bonding is generated in the cooling process.

Experiments were carried out on a fiber welding system. This system includes a 500 W fiber laser (1064 nm), a laser welding head, a 6-axis robot and an air-actuated clamper. The diameter of the focused laser beam is about 200 μm. To improve the heat conduction ability in depth and to avoid large thermal affected zone on the stainless steel surface, the defocused amount is set as 0 mm in the joining process. Joining parameters used in experiments are shown in Tables 1–3.

The clamper pressure is controlled by the air-actuated clamp and a 0–0.9 MPa pressure could be applied on the CFRTP-stainless steel sample. The SEM, EDS, the laser scanning confocal microscope and the electronic universal testing machine were applied to observe the joint microstructure, the joint thermal defect and the joint strength.

A 3 mm thickness CFRTP plate was used in this study. The matrix is PPS and the reinforced carbon fiber is T700, and the volume content of the carbon fiber in CFRTP is about 47%. The dimension of the CFRTP and the 304 stainless steel is 50 mm × 25 mm × 3 mm and 50 mm × 25 mm × 2 mm, respectively. Table 4 shows the thermal physical parameters of the PPS and the T700. Table 5 gives the chemical composition of 304 stainless steel. And the thermal physical parameters of the 304 stainless steel have been given in previous research [20]. Both the stainless steel and the CFRTP samples were cleaned by the absolute ethyl alcohol before joining to remove the greasy dirt. Three samples were joined and tested under the same joining condition to reduce the testing error.

The strength of the CFRTP/stainless steel joint was tested by the shear stress tester. The testing speed is 2 mm/min. Two heel blocks was tabled on both of the test sample ends for a convenient clamping (Fig. 2). After tensile testing, the joint melting width was measured by KEYENCE VX-X200 laser scanning confocal microscope as shown in Fig. 3. The joint melting width W_c is defined as the melting width of the CFRTP matrix, and the bonding area could be calculated by multiplying the melting width and the melting length.

3. Results and discussions

The CFRTP/stainless steel joining sample A3 is shown in Fig. 4 as the laser power, the joining speed and the clamper pressure is 280 W, 4 mm/s and 0.15 MPa, respectively. A clearly thermal affect zone is generated on the stainless steel surface because of the laser direct irradiation. However, the profile of the joint shows that a tight bonding is generated in the interface of the CFRTP/stainless steel, and there are no macro cracks and defects in the joint.

3.1. The stainless steel thermal defect zone

The thermal affect zone is generated on the stainless steel surface in the joining process. The microstructure and the strength character of the stainless steel may be changed because of this thermal defect. The joint sample is cleaned by a ultrasonic machine before tested by the laser confocal microscope to observe the thermal defect zone. It is found that lots of molten slag and oxides is

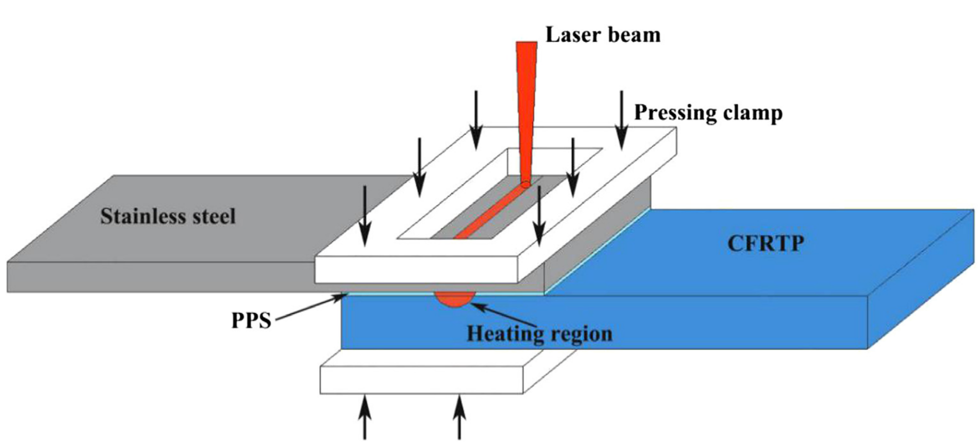

Fig. 1. Schematic diagram of laser joining between CFRTP and stainless steel.