Optics and Laser Technology 104 (2018) 73–82

Contents lists available at ScienceDirect

Optics and Laser Technology

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

Full length article

Experimental investigation into metal micro-patterning by laser on polymer-metal hybrid joining

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ARTICLE INFO

Article history:
Received 28 February 2017
Received in revised form 11 December 2017
Accepted 2 February 2018

Keywords:
Polymer-metal hybrid joints
Laser joining
Laser structuring
Glass fibre reinforced polymers
Mechanical performance

ABSTRACT

Surface modification pretreatment on laser direct joining of glass fibre reinforced polyamide to steel was studied to assess its effect on the joint's mechanical performance. The steel part was structured by laser radiation to accomplish a proper mechanical interlock when joining with the polymer. In a second step, the opposite side of the micro-structured metal was irradiated by a continuous wave (cw) fibre laser system until reaching the melting temperature of the polymer in both materials interface. The metal micro-structuring was produced by two different laser sources (nanosecond pulses (ns) and cw) in order to study the effect of different groove geometries on the joint's failure force under tensile-shear tests. The impact of structure density and clamping pressure was also assessed. A tight dependence of aspect ratio and recast material height of patterns on joint's failure force was found for the micro-patterns that were produced by nanosecond pulses. The greatest strength was achieved in the case of patterns produced by ns-pulses. The trend concerning the effect of structure density was validated for the patterns that were produced by ns-pulses and cw-radiation. The changes in clamping pressure did not evidence a significant influence on the joint quality. The morphological features of the detached surfaces showed that the micro-geometric structure aspect ratio has a meaningful effect on the failure mode in the case of structures that were generated by nanosecond pulses.

1. Introduction

Over the last five years, direct laser joining of plastic and metallic materials has attracted a considerable interest from a number of different industrial sectors such as automotive as well as in non-automotive applications, ranging from appliance housings to bicycle frames [1]. Depending on the optical properties of the polymer at the beam source wavelength, two variants exist. In laser transmission joining, the polymer is highly transparent to the laser radiation and the laser beam reaches the interface through the polymer without being absorbed. By contrast, in conduction joining, the polymer is opaque to the laser wavelength, so the metal surface opposite to the interface is directly irradiated by the laser beam, and the heat is transported by conduction to the interface, thus heating up the polymer.

The laser joining approach was first demonstrated at the Joining and Welding Research Institute of Osaka University by Kawahito et al. [2] and Katayama et al. [3]. In these pioneering studies, joints between stainless steel and PolyEthylene Terephthalate (PET), PolyAmide (PA), PolyCarbonate (PC) and PolyPropylene (PP) were generated. High tensile shear strength was achieved, suggesting the presence of both chemical and physical bonding. Since then, the technique has been extended to various material combinations, such as DC01 (SAE 1008) steel to PA6.6 [4], aluminium to PC, PA and glass fibre reinforced PA [5], AISI 304 stainless steel to PolyMethilMethacrilate (PMMA) [6], zinc – coated steel to carbon fibre reinforced PA [7] and stainless steel to Cyclic Olefin Polymer (COP) [8]. However, the direct laser joining of hybrid assemblies is still in development stage for industrial use and a deeper research has to be carried out. The mechanical performance of the produced assemblies has to be improved while the cycle time is reduced. The latter is directly related to the continuous development of high brightness laser sources.

Different approaches for polymer–metal hybrid joining were reviewed by Gruijic et al. [9], concluding that the one based on micro-scale mechanical interlocking is the most promising method. A way to further enhance the hybrid joint performance is to generate micro-patterns on the metal surface, so as to produce surface irregularities that provide an extra mechanical interlock with the melted polymer. Therefore, a greater control of the surface irregularities on a micrometric scale becomes important for hybrid polymer-metal joints. Laser microprocessing with pulsed sources is probably the most advanced technique developed for

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https://doi.org/10.1016/j.optlastec.2018.02.003
0030-3992/

micro-patterning mechanical components due to its inherent properties. For the last five years, several studies have been reported based on the effect of laser structure parameters on the mechanical properties of hybrid polymer-metal joints. Roesner et al. [10] reported the effect of structure density (defined as the ratio of the structured area to the overall examined area) generated during the laser metal micro-structuring on the mechanical behavior of hybrid joining (steel-PA) conducted by induction technique. Amend et al. [4] explored the hybrid joining of aluminium 5182 with three different thermoplastics (PC, PA6 and PA66-GF30). The study considered micro-structuring of the aluminium surface carried out by nanosecond laser pulses, analyzing the influence of two different surface textures (grid and craters) on tensile shear strength. Amend et al. [11] explored the direct joining between aluminium and PA6, performed by means of mono- and polychromatic radiation with the micro-structuring process produced by ns-pulses. They evidenced a clear dependence of the absorption percentage of aluminium with the micro-pattern density, being the pattern with the highest feature density the one showing the biggest absorption values. Heckert and Zaeh [12] reported the potential of laser processed surface structures in the macroscopic, microscopic and nanoscopic scale as metal pre-treatment for the subsequent thermal joining process of three fibre reinforced thermoplastics with aluminium. Taki et al. [13] reported the joining process of aluminium and three thermoplastics (PolyButylene Terephthalate PBT, PolyStyrene PS and Acrylonitrile Budatiene Styrene ABS) carried out by injection molding. They studied the effect of micro square grids generated on the metal by laser ablation and the injection parameters on the joint's mechanical performance. They evidenced three different failure modes directly related to the effective joined area. In a previous publication from the authors [14] the effect of geometric structures produced on metal parts on the mechanical behavior of steel-reinforced PA T-joints was analyzed. Structuring and joining operations were conducted by pulsed and cw laser radiation respectively. They identified the structure density and the pattern depth as the key parameters, while the joining area, structure orientation and alignment of the patterns did not affect strength values. Although previous studies demonstrated the effect of modifying the metal surface on the hybrid joint's mechanical performance, there has been no investigations focused on the influence of micro-patterns produced by two different laser sources on the joint's mechanical behavior or the use of the same laser source for the whole joining process. The kind of laser radiation has a direct impact on the pattern geometry to be produced on the metal specimen as consequence of the different laser-material interaction. Thus, it also influences the mechanical properties of the joint. On the other hand, the use of a single laser source for the whole process chain becomes significant to reduce investment costs and cycle times, essential points before up-scaling the process.

This research analyze the influence of metal groove micro-patterns on the mechanical performance of glass fibre reinforced PA (fibre content 30%) to HC420LA steel (DIN EN 10268:2013-12) unions in lap-joint configuration. The structuring process was conducted by pulsed and cw laser radiation, in order to produce different pattern geometries, while the joining step was carried out solely by cw use. The effect of different micro-features on tensile-shear force is discussed, along with the examination of the failure modes.

2. Materials, laser sources and experimental procedures

Materials used in this work were low-alloy steel HC420 and a glass fibre reinforced polyamide (PA6-GF30). Sample dimensions were 80 × 25 × 0.8 mm and 80 × 25 × 2.5 mm for metal and composite respectively.

Metal specimens were structured using two different fibre laser sources, the first operating in cw mode and the second in the nanosecond regime. Both beams were characterized experimentally to obtain the quality parameter M^2, which is a measure of the closeness to an ideal laser beam [15]. The M^2 value (Eq. (1)) quantitatively describes propagation, and is defined (according to ISO11146) as the ratio of its Beam Parameter Product (BPP) to that of an ideal Gaussian laser beam [15].

$$M^2 = BPP/BPP_{min} = \pi W_0^2/\lambda z_R \tag{1}$$

where W_0 is the beam waist radius, z_R is the Rayleigh range and λ is the operating wavelength.

Fig. 1 shows the corresponding laser beam caustics, disclosing two different propagation behaviors. The caustics clearly evidence better beam quality in the case of cw laser beam ($M^2{}_{CW}$ = 1.12) compared to the nanosecond laser beam ($M^2{}_{ns}$ = 2.68). Beam waist is also smaller in the case of cw laser beam (W_{0CW} = 13 ± 1 µm, W_{0ns} = 40 ± 10 µm). The latter along with the different temporal radiation characteristics for both laser beams produces different micro-pattern geometries on the metal part.

The cross sections of the specimens were mounted into Epoxy resin to analyze the depth, width and extent of recast material of the engraved structures by optical microscopy. Ten different measurements of groove depth, width and recast material height were carried out on each set of geometric structures, in order to guarantee a statistically reliable result.

The lap-joint configuration for the conductive joining process is shown in Fig. 2a. The top material (HC420) overlapped 20 mm with the bottom material (PA6-GF30). Both the structuring area and the joining track were 10 × 20 mm. The structuring zone was localized just below the joining track (Fig. 2a). The micro-structuring pattern was based on parallel grooves oriented perpendicular to the long edge of the plates. The joining operation was carried out using the same cw fibre laser system considered for the metal micro-structuring with a defocused 1 mm spot diameter. This spot was swept at high frequency for 10 mm, parallel to the long edge of the plate, using a galvanometric scanning system in order to generate an effective rectangular spot of 1 × 10 mm². The latter was then displaced at 360 mm/min in the same direction in which the grooves were produced, over the metal surface so as to produce a total joint area of 10 × 20 mm (Fig. 2a). Thus, the laser energy is first absorbed on the metal surface and then transferred by conduction to the surrounding area, melting the polymer and producing the joint after solidification. The joining process parameters

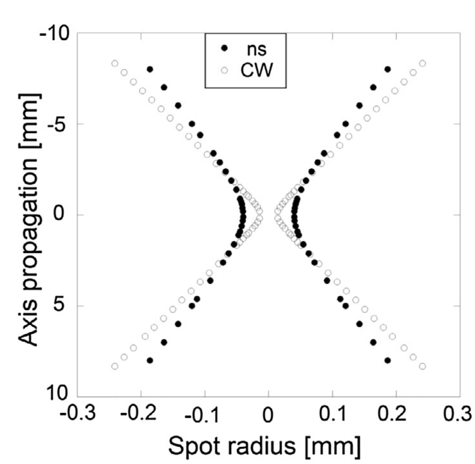

Fig. 1. Laser beam caustics for cw and nanosecond fibre laser sources.