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Recent advances in laser welding for joining polymeric components

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Abstract

Laser welding of polymers is a very popular industrial joining process, creating joints with good mechanical performance. However, the implementation of optimized laser welding processes is still quite limited since most industrial applications adopt an empirical approach to adjust the process parameters. The current work provides a summary of new findings on the subject of laser joining of polymers, describing the key operation modes of this joining method, its process parameters and how they affect the joint characteristics. The response of polymers to temperatures generated during laser welding is also discussed, as well as the effect of additives on the weldability of polymers.

1. Introduction

The use of laser welding as a joining process is still a relatively recent activity (Katayama, Kawahito, and Mizutani 2012) but already finds use in a wide range of applications, any of those in the automotive industry and the electronics sector. In these applications, laser welding is extensively used to create highly complex products, including those which rely on welding of dissimilar metals, metals with very low weldability (Sakamiti et al. 2019) and metals to polymers (Katayama and Kawahito 2008; Lambiase, Genna, and Kant 2018). Furthermore, some advanced applications use laser-welding to successfully achieve the task of joining ceramic materials (Hirsch et al. 1998; Song et al. 2019), doing so by exploring the extremely concentrated energy input that this process provides. Nevertheless, one of the key applications of laser welding in industrial settings is still polymer-to-polymer joining of components, especially those composed of thermoplastics (Duley and Mueller 1992; Jansson et al. 2003; Wissman 2007). When this joining process is correctly implemented, laser welded joints exhibit good mechanical performance, are free of flaws and defects, and practically invisible. In fact, this last consideration has a very significant impact in modern production processes, where aesthetic concerns have a high degree of importance. This manuscript provides an outlook on the most important research activities on this field and summarizes the main conclusions and recommendations with impact in practical application of polymer laser welding processes.

2. Operation modes in laser welding of polymers

Laser welding entails the use of a highly coherent light beam to transfer a very large amount of thermal energy to a very localized region of the joint. The materials to be joined are fused together and, when the laser energy is removed, the materials solidify, and the desired joint is created. It is important to note that laser welding of polymers is carried out mainly in two different modes of operation. In this first mode, industrially known as contour welding (Figure 1a), both materials to be welded have a large capability to absorb laser radiation and convert it into thermal energy (large absorption). Thus, the laser light is used to fuse them equally and simultaneously. The second mode, known as transmission welding (Figure 1b), considers welding of materials with very different response to laser light, where one of the materials has a large absorbance and the other is transparent to laser light (a high transmittance). These materials are then stacked, with the transparent material placed over the absorbent one. When the welding process begins, laser light travels unimpeded through the transparent material until it reaches the laser absorbent material. Here, the laser energy is released solely at the interface between the two materials. The absorbent material heats up and transfers some of this heat to the transparent material, resulting in the simultaneous fusion of both base materials. A variation of this process (Figure 1c) uses two similar laser transparent materials stacked but introduces a special coating on the upper surface of the lower transparent material, which acts as a barrier for the transmission of the laser light and thus creates a point where thermal energy can be released.

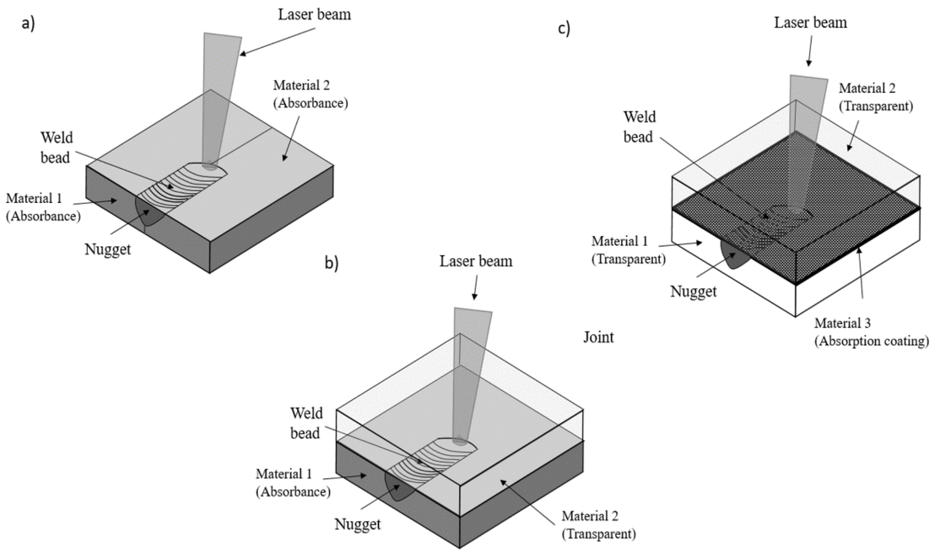

Figure 1: Different modes of operation of a laser welding procedure a) contour welding of two equally absorbent polymers; b) transmission welding of two polymers with different levels of absorbance and c) transmission welding of two transparent polymers with recourse to an absorption coating material

3. Effect of process parameters of laser welding of polymers

A wide range of parameters is associated with the laser welding process, with significant implications in joint strength and the suitability for practical implementation of the process. The most important of these parameters are the wavelength of the laser light provided by welding equipment, the incident power, the pulse frequency, length and shape and the travel velocity, although this list is in no way exhaustive since many others exist. Although tuning of these parameters in industrial applications is often carried out in an empirical manner, driven by experience, several recent research works have been devoted to the study of these parameters and the effect they have on joint performance. The work of Hubeatir (2020) focused on the study on the welding speed, bead depth and width during welding of a polymethyl methacrylate (PMMA) polymer. The authors identified an almost linear relationship between these parameters, determining that the width and depth of the bead follows and inversely proportional trend when plotted against the welding speed. However, it is noticeable that for low welding speeds the bead width remains stable, only decreasing linearly for large weld speeds. A schematic representation of these results is provided in Figure 2.

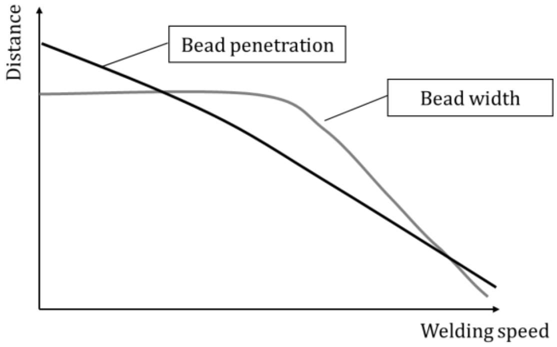

Figure 2: Schematic illustration of the dependence of the bead depth and width as a function of the laser welding advance speed

It is possible to analyse heat transfer equations to precisely determine the expected width and depth of a laser weld bead. The work of Taha et al. (2009) adopted such approach, analytically determining that the very high advance rates will always correspond to a reduced width and depth of the bead, even if other parameters are adjusted accordingly. Finite element analysis can also be exploited for this purpose, allowing to more dynamically model heat transfer processes associated to welding. The work of Acherjee et al. (2012) and Casalino and Ghorbel (2008) used FEM to determine the effect of the incident laser energy on the shape of the weld bead, finding an almost linear correlation between the energy and the width of the bead. Ruotsalainen, Laakso, and Kujanpää (2015) performed an experimental study, focusing on the effect power input during welding of a polyamide using a 1940 nm wavelength diode laser, finding a similar correlation between input energy and bead shape.

4. Polymer response to laser welding

One key aspect of the laser welding process is the effect of the incident energy on the properties of the base materials which induces a phenomenon which is analogue, but unrelated, to the heat affected zone formation in fusion welded metals. Experimental processes to control and qualify the thermally affected zone in laser welded polymers make use of pyrometers to correlate the temperature fields and gradients with the regions of the polymers which are thermally affected. A study of this type conducted by Schmailz et al. (2020) has shown that it is possible to precisely model this affected zone and correlate this effect with the properties of the base material. Further work has been carried out on this subject by Hubeatir (2020), showing that the addition of infrared thermography is also suitable to perform these types and correlations and detect flaws and defects on the welded region, including the presence of pores and the existence of gaps between the welded parts, as well as other geometrical defects. Laser welding of fibre reinforced thermoplastics, such as polybutylene terephthalate reinforced with glass fibre (PBT-GF30) poses important challenges related to the interaction of the laser radiation with the polymer and with the glass fibres. The authors have studied the behaviour of a laser welded PBT-GF30, subjecting it to a series of thermal treatments that reproduce the thermal effects of laser welding, with the results being shown in Figure 3. There is an evident decrease in both the stiffness and the maximum tensile stress sustained by the material as well as the strain at failure, with a major drop in strength and stiffness for the temperature of 257 °C, as the degradation temperature of the material is achieved.

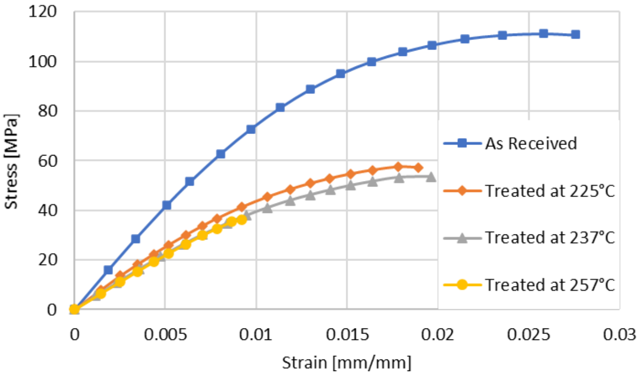

Figure 3: Tensile response of laser weldable PBT GF-30 material to different temperature temperatures

The process of degradation is the result of a damaging interaction between the fibre reinforced material and the energy supplied by the laser radiation. Materials which are subjected to laser welding will exhibit higher pore density, with transversal sections of the fibres being fully exposed. Significant surface voids will also appear, resultant from the intense fusion and solidification cycle. All these effects have a deleterious effect on the load bearing capability of the fibre reinforced polymer and thus demonstrate the importance of reducing the area where heat is applied.

5. Additives for enhanced laser weldability of polymers

The addition of particles or other materials can also be carried out to purposely alter the properties of the laser welded materials, changing their response to the laser radiation (Schmailzl et al. 2020). This is useful, for example, in applications based in transmission laser welding processes, as described in Section 2 of this document. Diverse experimental works have been devoted to this aspect, such as the work of Chen, Zak, and Bates (2011), which experimentally determined the effect of the adding carbon black particles to laser weldable thermoplastics. The laser light absorption coefficient was found to increase linearly with the carbon black content. This was found to be true for polyamide, glass fibre reinforced polyamide and polycarbonate, as shown in Figure 4. Acherjee et al. (2012) performed a similar study, correlating the increasing energy absorption attained with carbon black particles with the shape of the weld bead. Gisario et al. (2017) carried out additional work on the effect of carbon black, considering polyethylene terephthalate (PET) materials with different percentages (in weight) of carbon black particles, ranging from 5% to 15%. The authors found that the addition of larger contents of carbon black had a very noticeable impact in reducing the area degraded by to high temperatures, even under larger incident power levels and lower advance speeds. This allows to increase the effective welding area without severely damaging the material.

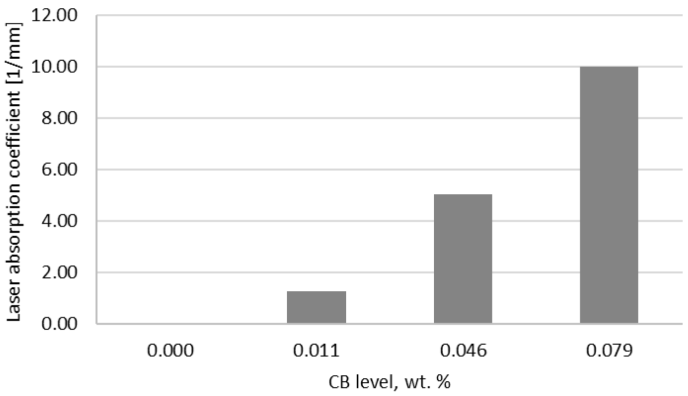

Figure 4: Variation of the laser absorption coefficient of polycarbonate as a function of the added amount of carbon black particles

The use of carbon-nanotubes (CNTs) also has a significant impact on the absorption of laser energy for some polymeric materials. Rodríguez-Vidal, Quintana, and Gadea (2014) experimentally tested the effect of the effect of CNTs on acrylonitrile butadiene styrene (ABS) welded with a 880 nm diode laser. A noticeable in improvement in laser absorption was found, in addition to the already improved mechanical properties of the base material conferred by the addition of CNTs. The work of Chen, Zak, and Bates (2011) followed a similar experimental approach, and also analysed the effect of the presence of CNTs on the electrical resistance of the material, which can act as a proxy for the energy conductivity and absorption levels. The authors demonstrated that a CNT content of 0.05% in weight leads to significantly more resistant joints due to improved energy absorption and wider and deeper beads for the same amount of incident laser energy.

6. Conclusions

Laser welding of polymers is nowadays seen a very powerful and advantageous process, with good mechanical capabilities and high flexibility. It is also growing in popularity as the price of laser welding equipment decreases. However, in most industrial applications, only a limited optimization of the process is made, following an empirical analysis. Scientific practice has demonstrated that it is possible to design laser welding processes in a more analytical manner, using, for example, finite element analysis to effectively simulate the heat distribution in a laser welding procedure and correlate the heat distribution with both the key process parameters and the effect of temperature on the properties of the heat affected material. Furthermore, the use of additives can be effectively explored to achieve specific operation modes that allow for the creation of joints between dissimilar materials that cannot be achieved with any other joining process.

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