Optics & Laser Technology 91 (2017) 80–84

Contents lists available at ScienceDirect

Optics & Laser Technology

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

Full length article

Laser transmission welding of polylactide to aluminium thin films for applications in the food-packaging industry

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ARTICLE INFO

Keywords:
Laser transmission welding
Bonding
Polymer
Aluminium
Thin film

ABSTRACT

Laser transmission welding is a suitable technology to join thin films of similar or dissimilar materials without any addition of chemical solvents or adhesives. This process represents a very important opportunity in the case of packaging applications (for example in food and pharmaceutical sectors) where the realisation of strong welds by avoiding the contact between the thermal source and the processed materials and, furthermore, without using any third material that could contaminate the contents, is reliable and relevant.

The aim of this paper is to prove the feasibility of the laser transmission welding of polylactide to aluminium thin films by means of laser transmission welding through the use of a low power pulsed wave fibre laser. Laser joint samples were realised, analysed by optical microscopy to reveal possible defects and to evaluate the weld width and tested to measure the mechanical tensile strength. An accurate relationship between the joint quality and both the welding speed and the *k*-factor, which represents the delivered energy per unit length and affects the bonding mechanism at the interface, was determined. The achieved feasibility area is extremely narrow and possible only for the higher value of the average power. The joint tensile strength was proven to be in a proportional relationship with the effective bonded area and reached satisfactory values.

1. Introduction

1.1. Concerning the laser welding of polymers

Laser welding is generally a precise and accurate technology that has a number of advantages in comparison with conventional joining technologies for polymers, such as adhesives, hot plates, ultrasonic and/or vibration welding processes. The joining tool allows a non contact process, which is specifically useful to join thin films of similar or dissimilar materials in the case of the food-packaging industry because a direct contamination, which can occur in the case of a direct contact with the thermal source, is avoided. Besides, the use of any third material between the two parts to be joined is typically not necessary. These features are very significant for packaging applications in the food and pharmaceutical sectors or medical devices, where the solvents or adhesives have several drawbacks such as shrinkage during curing and/or lack of biocompatibility. In addition, the seals could have high mechanical strength, longevity and aesthetic appearance [1].

Lasers can also be easily implemented and integrated into existing production lines and typically allows the realisation of highly flexible manufacturing systems.

Polymers are usually laser welded by overlapping; the laser energy is partially absorbed into the material and converted into heat that locally melts the irradiated material and generates chemical and/or mechanical bonds. A clamping pressure is usually necessary and can be crucial to ensure the contact during the heating phase and the joint formation.

Based on the wavelength of the laser beam, two methods for polymer welding are possible: absorptive welding and transmission welding [2]. In the absorptive welding method, when it is performed by CO_2 laser sources with a beam wavelength equal to 10.6 µm, the energy is absorbed by the upper part that is directly irradiated and the interface is melted by heat conduction [2]. Due to the typical high absorption of polymers at the wavelength of a CO_2 laser, the irradiated part can be prone to defects such as burns, damages, perforations and degradation reactions may also take place. So, the use of this method for bonding thin films could produce joints with an inadequate quality.

In the transmission welding method, the irradiated upper part must be transparent for the incident laser radiation (in this case, typical wavelengths are from 0.8 µm up to 1.1 µm) and the lower part must be absorbent. The laser radiation passes through the upper component

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http://dx.doi.org/10.1016/j.optlastec.2016.12.014
Received 18 May 2016; Received in revised form 6 December 2016; Accepted 17 December 2016

and is absorbed at the interface by the lower part and heats up the upper part by conduction, thus ensuring the bonding. To improve the absorption of the lower part, appropriate additives can be used, namely IR-absorbers, which influence the optical properties of polymers in the Near-Infrared field. For example, the high beam energy absorption of carbon black powder has a great influence on the temperature field distribution, affecting the formation and the shape of the weld pool geometry and also the strength of the weld [3]. This method cannot be applied to join two transparent parts.

This paper describes the experimental results of a study concerning the laser transmission welding of a PolyLactide Acid (PLA) thin film to an aluminium film for food packaging by using a 20 W Pulsed Wave (PW) fibre laser with the aim to identify the process feasibility area.

1.2. Concerning laser transmission welding

The laser transmission welding of polymeric thin films to metal films involves complex physical phenomena that influence the joining mechanism at the interface [4]. The generated heat by means of the interaction between the laser beam and the material, warms up and melts the polymer, which interacts with the metallic surface and forms both mechanical and chemical bonding. Katayama and Kawahito demonstrated that the bubble formation in the molten polymer supports the adhesion by a mechanical mechanism to the metal surface by means of the increase of the local pressure of the molten polymer [5]. The chemical bonding at the interface has been identified in [6] by the use of X-ray photoelectron spectroscopy (XPS) for different pairs of materials. It was found that the joint-quality depends on a huge number of process parameters such as laser power, pulse repetition frequency, pulse duration, beam diameter and welding speed, as well as on material properties such as thermal conductivity, specific heat, density, laser absorption coefficient, reflectivity and transmission factor. A strong joint was formed in any case when the thermal energy generated by the laser beam was sufficient to activate the bonding mechanism.

The main effect of laser heating is a rapid increase in temperature that must be controlled in order to maintain a range between the melting point of the polymer and the temperature at which degradation reactions take place. Predicting the effect of process parameters on joint quality by measuring the temperature profiles during the welding process can be difficult. In scientific literature, numerical models were proposed to simulate the physical processes and to predict the temperature distribution at the interface. A finite element model to determine the optimum condition to bond polyimide (0.18 mm thick) and titanium (0.05 mm thick) films was developed by Mahmood et al. [7]. Mayboudi et al. showed that beam scatter is an important factor in the thermal modelling of the laser transmission welding process [8]. They defined a 3D transient thermal model for a lap-joint for commercial polyamide-6 (transparent PA6 to PA6 with a 0.2% of carbon black) by using a diode laser with a rectangular uniform beam energy distribution. The numerical results, in terms of temperature distributions and weld dimensions, were compared with the experimental data and a good agreement were obtained only if the laser beam scattering during transmission through the polymer is considered in the model. Also, Acherjee et al. defined a 3D model for the prediction of the temperature field at the interface and the weld dimensions for the laser transmission welding of PolyVinyliDene Fluoride (PVDF) foils to titanium foils [9]. This model can also be used to determine an optimum combination of laser power and laser welding speed for welding a specific set of dissimilar materials. A systematic investigation by using a finite element analysis and techniques for the design of experiments was carried out by the same authors [10].

Empirical models based on simulation results, were implemented to evaluate the effect of process parameters such as power, welding speed, beam diameters and carbon black content on the weld characteristics. The materials considered were natural and opaque polycarbonates. The response surface methodology was used by Wang et al. to optimize a laser welding of PolyEthylene Terephthalate (PET) films and AISI 316 L sheets using a CW diode laser [11] or PET film and titanium [12]. The predicted values of the joint strength were in a good agreement with the experimental result.

Fiorini et *al.* studied the weldability of the PLA, through the comparison of the laser transmission welding with a solvent-based technique in [13]. The purpose was the comparison of the joining efficiency between PLA thin films with different percentages of an impact modifier to improve toughness and material processability.

2. Materials and experimental approach

The investigated materials, the experimental approach and some methods proposed for joint characterization are described in the following sections.

2.1. Materials

PLA is a highly eco-friendly and a very versatile polymer. It can be used to replace non-biodegradable plastics in packaging products such as films, cups, dishes, disposable cutlery and in general when degradability and recycling are the most required properties. Recently, PLA has been employed in casings of smartphones, tablets and other parts of electronic equipment. PLA can be processed using standard technologies applied to thermoplastic materials such as injection moulding, thermoforming, foaming, extrusion casting for films and slabs, blown film, stretch blow moulding for bottles and electro-spinning. Only minimal modifications are necessary to make possible the use of standard equipment. However, PLA presents a higher fragility and lower barrier properties than petroleum-based polymers. Besides, PLA undergoes hydrolysis at high temperature in presence of moisture that can compromise its physical properties [14]. For this reason, a careful drying is mandatory before processing. Currently, PLA films are mainly applied in packaging, for examples pouches for organic vegetables and labelling. At the moment the market volume is still small but many studies forecast a rapid growth in the use and in the production volume of PLA films in next few years.

The aim of presented experiments is to join a 75 µm thick commercial PLA film - produced by Sidaplax v.o.f. - to a 25 µm thick aluminium foil for food-packaging application by using a fibre laser. The metallic film is made of annealed pure aluminium, EN AW-1050A [Al 99.5] according to DS/EN 546-2. The relevant material properties of the two employed materials are reported below (Table 1).

2.2. The experimental setup

The experimental setup exploited in the reported activity is based on an IPG YLP Q-Switched fibre laser source, with a maximum average power of 20 W, wavelength equal to 1.064 µm, M^2 =1.1, minimum spot size 50 µm. The system is equipped with an Aerotech PRO1153-axis

Table 1
Properties of tested materials.

Material	Properties	
PLA commercial film	Thickness [µm]	75
	Morphology	Semi-crystalline
	Density [g/cm^3]	1.24
	Melting Point [°C]	145–160
	Glass Transition Temp. [°C]	55–60
Aluminium film	Thickness [µm]	25
	Density [g/cm^3]	2.71
	Melting Point [°C]	643 – 660
	Specific Heat Capacity [J/g-°C]	0.904