Applications of laser welding for the joint of plastic materials

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Abstract

A pulsed infrared laser source, like the Nd:YAG, welds the irradiated plastic materials by means of a thermal process that gives a direct chemical bond between two layers in close contact each other. The intense photon radiation, of the order of 10^{10} W/cm^2, is capable to modify the polymeric materials inducing a melting process that seals two sheets at their interface. The sealing action occurs between the polymeric layers if one of them, placed in second plane, can absorb the laser light while the other, placed in first plane, is radiation transparent. The polymer filler presence (like carbon nano-structures, iron oxide, silicate,...) is required in order to absorb the laser light and to obtain the joint at the interface with other polymers through an accurate control the filler concentration. The penetration depth of the laser light and the mechanical resistance can be regulated by the absorption power of the polymeric layer. With this aim, the filler amount must be accurately chosen in order to produce a strong joint. In this work we investigated the applications of Nd:YAG laser welding for the polyethylene biomedical joint devices. In particular, we examined the possibility to define the optimal depth of the sealing action by regulating the filler type and amount in different joint geometries.

Introduction

Laser technology offers many advantages in the welding of plastics. The Through Transmission Visible Laser Welding (TTVLW) process involves localized heating at the interface of two pieces of plastic that will be joined. This method produces strong and hermetically sealed welds with low thermal and mechanical stress, without particulates. Only some materials and combinations of materials are suitable for transmission laser welding because this method needs an optically transparent plastic layer and another absorbent.

There are various methods to make the plastic able to absorb the laser energy, such as the use of nanostructures embedded in the polymer which have high absorption at the used laser wavelength. Additives such as carbon nanotubes (CNTs) nanostructures of Fe_2O_3 or methylene blue for example, can be used to color with black, red or blue respectively, the polymer sample and to increase the visible laser absorption in the first sample layers [1].

Laser light penetrates the upper layer and it is absorbed by the lower material. The melting of the latter transfers the heat to the upper layer. The mutual melting pool solidifies under

external pressure to a high-quality weld [2]. For this reason the pulsed laser welding of polymers depends strongly on the optical characteristics of the coupled polymers [3].
Different laser sources are commonly employed for the welding of polymers, such as continuous CO_2 high-power infrared lasers at 9.4 and 10.6 μm wavelengths, ns pulsed Nd:Yag lasers, generally employed at the second harmonic of 532-nm wavelength, and high-power semiconductor diode lasers, with small dimensions and generally employed in the visible emission range [4].
Many thermoplastic polymers can be joined by laser sources, such as polyethylene, polyvinylchloride, polyethylene terephthalate, polymethylmethacrylate and acrylonitrile butadiene styrene. Often these polymers must be coated or filled with nanostructures, in order to control their absorption coefficient with respect to the used laser wavelength.
The main process parameters that affect the bond quality are: the laser power, the welding speed and time, the laser beam size and uniformity, the adsorption properties of the polymeric materials at the interface of the two polymers and the pressure of clamping.
In this work we studied blends made by polyethylene, a versatile thermoplastic material, doped with different fillers (iron oxide, carbon nanotubes and methylene blue).
We presented some preliminary comparative results about the physical analyses and the mechanical characterization performed on the laser welded joints, with the aim to study the effects of the kind of filler on the welding features. Different geometries available through TTLW and some applications are presented and discussed in the paper.

Materials and methods

Materials

The polymeric matrix was an Ultra High Molecular Weight Polyethylene (UHMWPE resin, Ticona-GUR 1020: $M_w \approx 3\times10^6$ g/mol and particle powder size of 150 micron, code "UHMWPE". The fillers were:

- Multi walled carbon nanotubes (MWCNTs): obtained by Chemical Vapor Deposition (CVD) technique, with an aspect ratio (l_n/d_n)of 1000 and purity >95% (code: "CNT");
- Iron oxide, supplied by Across Organics with a purity level of 99.999%, particle size of ten nanometer order (code: "Fe_2O_3");
- A glass matrix of calcium silicate with high porosity (particle size < 75μm and surface area= 70-100 m^2/g) where the organic pigment of methylene blue hydrate (supplied by Fluka) is entrapped, (code: "BM").

The composites were made by following the schema in fig. 1:

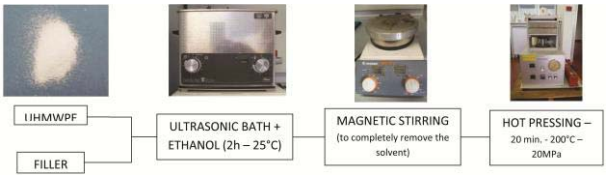

Figure 1 – Flow sheet of the preparation steps of the filled polymer.

Some features of the studied samples, like the appearance, the density, ρ, and absorption coefficient (at 532nm and with 1wt% in weight of filler), μ, are resumed in Table I.

MATERIALS	COLOR		ρ (g/cm^3)	μ (cm^{-1})
UHMWPE	Semi-trasparent		0.930	5.0
UH/BM.	blue		0.938	5.6
UH/Fe_2O_3	Red		0.9340	184
UH/CNTs	Black		0.944	380

Table I- Materials features

Laser irradiation process

The polymeric targets were irradiated in air at room temperature (25°C) for 2 minutes by a

3-ns Nd:Yag laser operating at 532 nm (second harmonics) or at 1064 nm, in a single pulse or at 10-Hz repetition rate, with an intensity of 1.8 x 10^8 W/cm^2, a maximum pulse energy of 150 mJ and a laser spot of 28 mm^2 (no focusing lenses were employed). The laser pulse energy has a Gaussian shape with a diametric FWHM of about 3 mm. The incident angle of the laser beam was 0°.

The welded joints were obtained by coupling two rectangular polymeric sheets, partially overlapped for a length of 15 mm. In particular, the UHMWPE sheet, highly laser transparent, was placed on the top (irradiated face) while the highly laser absorbent sheet (UHMWPE + colored filler) was placed on the bottom (un-irradiated face) and pressed each other with pressure of ≈ 180 kPa.

Characterization analyses

The Absorption Percentage of the laser light was measured through the Optical carried out on thin polymeric sheets (90 µm thickness), filled and un-filled, at different wavelength, from 240 nm to 1060 nm.

The absorption percentage was calculated by the following formula:

$$A = 100 - T \qquad (1)$$

where A = absorption percentage, T = I_T/I_0 transmittance percentage, where I_0 = incident laser intensity and I_T= transmitted laser intensity.

The mass quadrupole spectrometry (Balzer MQS 300) operating between 1 and 300 amu range with sensitivity higher than 1 ppm was employed. The MQS measurements were obtained by irradiating the different polymers in high vacuum conditions (10-6 mbar).

The shear test was carried out on the joints at 25°C by a LLOYD LR 10K universal testing machine with a crosshead speed of 5 mm/min. The specimens had a rectangular geometry, 20mm x 30 mm and 1 mm of thickness. For each kind of filler 10 specimens were tested in order to give the average value.

Results

Optical spectroscopy measurements: the absorption power of the pure PE changes after the filler addition in the order:

PE<PE/BM<PE/Fe_2O_3 < PE/CNTs

and it decreases from the lowest wavelengths (UV region) to the highest one (IR region) as plotted in the graph of fig.2.

The knowledge of the absorption power of the materials in a wide spectral range, from UV to IR wavelengths, is important to optimize the interaction between radiation light and targets and to generate hot laser plasma. The plasma properties are strongly dependent on the laser intensity and wavelength.

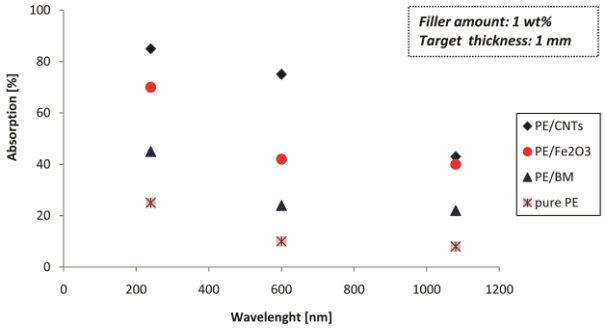

Fig. 2 - Absorption percentage of pure and filled UHMWPE at 240, 600 and 1080 nm.

The effects that the laser light can produce on a generic target are the following:

- long wavelengths, such as infrared radiation, generally induce thermal effects. Heating, vaporization, thermal diffusion and sublimation occur in the target;
- short wavelengths, such as ultraviolet radiation, generally induces chemical effects: breaking of bonding (scission), molecular dissociation, radical formation, molecular cross-linking and chemical reactions;
- visible radiation could induce both thermal and photochemical effects depending on the wavelength and target composition [5].

The filler presence in a polymeric material, like polyethylene, greatly increases the laser light absorption.

CNT filler is the most capable to absorbs the UV, Visible and IR light, while the BM is the worst among the tested fillers.
MQS spectra were recorded during the laser irradiation process of a UH/CNT (1wt%) sheet at 532 nm (visible light). The MQS spectroscopy detect the gas species emitted from the polymer during the laser irradiation.

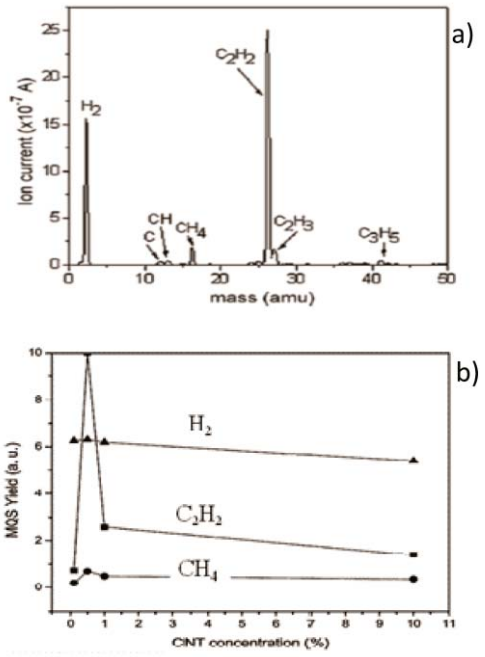

Fig.3 - MQS spectrum of a UH/CNT (1wt%) sheet at 532 nm(a); MQS yield of H_2, C_2H_2 and CH_4 species in the UH-CNT samples vs filler concentration (b)

As example, MQS spectrum of UHMWPE + 1% CNTs is shown in fig. 3a.
The MQS results show that the H_2 and C_2H_2 are the main desorption gasses emitted during the laser ablation. The presence of different C_xH_y groups (CH_4 groups, for example) in the MQS spectra indicates that a complex chemistry contributes to the macroscopic welding because a molecular re-organization, due to C-C and C-H bond breaking, occurs.
The height of the peaks is a complex function of the CNTs concentration, as reported in the measurements plotted in fig. 3b. So, we can suppose that the polymer welding is partially associated with the thermal processes, that occurs at the interface of the sheets, but photo-chemical and ion implantation effects carry out an important role, too. So, the MQS result has confirmed the optical spectroscopy results above discussed. The Nd:Yag laser source modifies the polymer and generates an energetic process that develops heat, ions, radical species and new chemical rearrangements. These processes involve mainly thermal melting, and other processes, such as chemical processes, which promote the polymeric chain adhesion.
The typical force/deformation curve obtained during a shear test is shown in fig. 4.

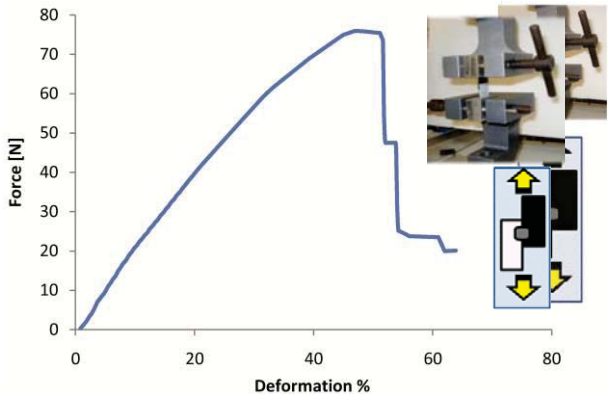

Fig. 4 - Typical force/deformation curve of a joint UH-UH/B.M. In the frames: magnification of a joint during a shear test (above) and force directions applied to the welded sheets (below).

The choice of the best amount of filler in the polymeric matrix and the best wavelength of the laser beam is important to the strength of the joint. In fact the deepness of the welding can be regulated modifying the filler amount: low filler amount generate strong seal, while weak seal occurs with high filler quantity.
In our case, UH/UH-CNTs and UH/UH-Fe_2O_3 are realized with a laser beam operating at 532 nm and with 5wt% of filler. While, UH/UH-BM is realized with a laser beam at 1064 nm and with 10wt% of filler. A higher amount of BM is essential because it has the lower coefficient absorption than the other fillers. Preliminary results of the shear test (fig.5) show that, on the equal irradiation time (5 minutes), the force necessary to break a UH/UH-CNTs joint (≈ 145N) is slightly more than the break force of a UH/UH-Fe_2O_3 joint (≈ 142 N). On the contrary, the UH/UH-BM

shows a weak break strength and the shear force become ≈ 80N.

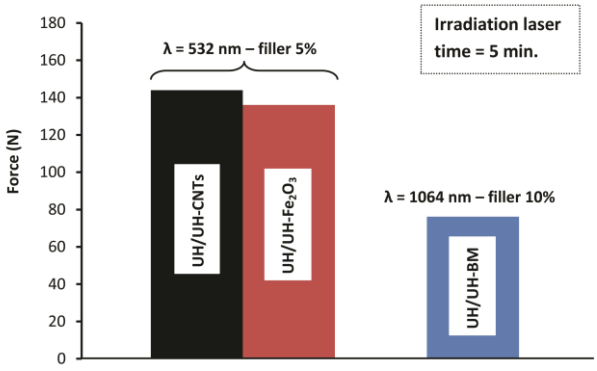

Fig. 5 – Comparison of the shear force at the same irradiation time (5 minutes) of the joint realized with different fillers and at different λ.

In order to improve the adhesion force, the welding of sheets with B.M. should be make in the visible or UV region, according to the result of fig. 2.

Laser welding of polymers is becoming an alternative to conventional technologies and it can be applied to different geometries and in several fields (fig. 6), including: biomedical devices, textiles, food and medical packaging, etc.

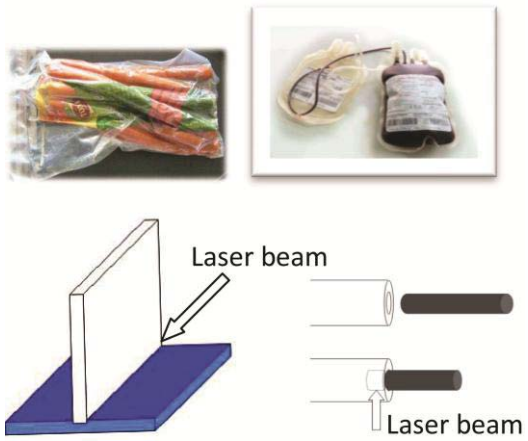

Fig. 6 – Examples of industrial application of laser joints (above) and possible geometries of plastic joints (below)

Different geometries, like tubular or "T joint", can be represent some examples of application of the laser welding in which the precision of the seal and the absence of particulate are appreciated. In these cases, we can observe that the thickness of the joint can be very different. Anyway, all these examples highlight the different geometries require different sealing features with different deepness of modification of the materials.

Conclusions

The Nd:Yag laser source modifies the polymer in the contact area, generating an energetic process that develops heat, ions, radical species and new chemical rearrangements. These processes improves with increasing the absorption power of the filler. They involve mainly thermal melting, but there is experimental evidence of other processes, such as chemical ones, which promote the polymeric chain adhesion. Work in progress in order to investigate more deeply on :

- the joints UH/UH-BM by changing the filler load , irradiation time, wavelength;
- new joint realized with other materials (for example PMMA, PP, PEEK, Teflon, PS, etc..);
- the different mechanism (physical and chemical) that are occurring during the laser irradiation.

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