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Welding of polymers using a 2 μm thulium fiber laser

Ilya Mingareev [a,*], Fabian Weirauch [a,b], Alexander Olowinsky [b], Lawrence Shah [a], Pankaj Kadwani [a], Martin Richardson [a]

[a] Townes Laser Institute, CREOL, University of Central Florida, Orlando, FL 32816, USA
[b] Fraunhofer Institute for Laser Technology, 52074 Aachen, Germany

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ABSTRACT

Absorber-free transmission and butt-welding of different polymers were performed using thulium fiber laser radiation at the wavelength 2 μm. The relations between the laser process conditions and the dimensions and quality of the seam were investigated by means of optical and phase-contrast microscopy. Mechanical properties of the weld joints were studied in tensile strength tests. Laser-welded polyethylene samples revealed a tensile strength of greater than 80% of the bulk material strength. Transmission welding of different polymer combinations featured the formation of different joint classes depending on the spectral properties. The experiments demonstrate new application areas of mid-IR fiber laser sources for materials processing.

1. Introduction

Since the mid-nineties of the last century, laser welding has become a common method for joining polymers. Today a large selection of thermoplastics can be processed with a wide range of appropriate laser sources utilizing this contactless technology that allows an effective, space-selective energy deposition. Despite its general acceptance and utilization in mass production and high-accuracy assembly for a wide variety of industrial applications, continuous research efforts in laser polymer welding are focused on process optimization [1], development of novel processing strategies [2] and laser sources [3], and different material aspects of polymer joining [4].

In recent years a new class of high-power fiber laser systems has been developed [5]. These laser systems utilize thulium-doped fibers pumped by high-brightness 793 nm laser diodes. The emitted laser radiation has a wavelength around 2 μm, which enables new process windows for laser welding of polymers based upon different absorption properties compared to the visible and near-infrared wavelength ranges. For some materials, efficient welding using laser radiation at the commonly used wavelengths around 1 μm is only possible with additives that increase the absorption of the laser radiation [6]. Using additives may considerably increase the number of required process steps and therefore the overall manufacturing costs. Furthermore, their utilization is sometimes prohibited in bio-medical applications due to the toxicity of the additives. Lastly, additives can influence the color of the polymers, which might be a critical factor for a particular application. In contrast, laser radiation produced by Tm-doped fiber lasers offers high continuous-wave output powers and good beam quality that can be directly absorbed in the material. Additionally, the wavelength of 2 μm is in the so-called "eye safe" spectral region, which may support the general acceptance of Tm-fiber lasers in industrial environment. This is due to the high absorption of laser light in the eye's cornea in this spectral region. Thus the laser light cannot threaten the high sensitive retina.

In this paper, butt-welding of low- and high-density polyethylene (PE-LD, PE-HD), polymethylmethacrylate (PMMA), polypropylene (PP), polyoxymethylene (POM) and glycol-modified polyethyleneterephthalate (PETG) using continuous wave laser radiation at 2 μm was studied. Additionally, a feasibility study of transmission welding of PETG, PMMA, and combinations PMMA/PP and PP/PE-LD was performed. In all the experiments intrinsic absorption of polymers was utilized for welding without adding any IR-absorbers. The resulting weld quality was investigated by means of optical, phase-contrast and polarization microscopy at the weld cross-sections. The tensile strength of butt-welded materials was measured and compared to that of a corresponding bulk material.

2. Experimental details

2.1. Laser setup

The laser source is a self-developed Tm-fiber laser system emitting non-polarized laser radiation with a wavelength $\lambda = 2\,\mu m$, beam quality $M^2 < 1.2$, power stability $< 2\%$ over 1 h, and a maximum

* Corresponding author.
E-mail address: mingareev@ucf.edu (I. Mingareev).

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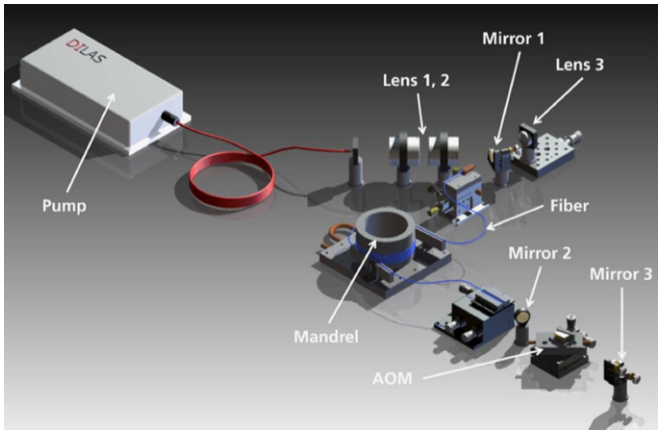

Fig. 1. Schematic setup of the Tm-fiber laser system.

output power of $P=27$ W (Fig. 1). A fiber-coupled pump diode with a maximum output power of 100 W and a wavelength of 793 nm is used for pumping a thulium-doped silica fiber. The output of the pump diode is first collimated and then focused, using two fast achromatic doublet pairs (Lens 1 and 2). The laser radiation is reflected from a dichroic mirror (Mirror 1) into the Tm-fiber. This mirror is highly reflective for wavelengths near 790 nm and highly transmissive for wavelengths from 1.9–2.1 μm. The laser active fiber is 4.5 m in length, and has a core diameter of 25 μm and a cladding-diameter of 400 μm. It is wrapped around a mandrel of 11 cm diameter which is cooled to approximately 14 °C in order to improve laser efficiency and prevent thermal damage. The active fiber is spliced to ~1 m long sections of passive fiber at each end so that it is possible to water-cool the complete length of active fiber. The fiber facet being pumped is held in a water-cooled mandrel to minimize thermal damage to the fiber's polymer coating from stray light.

For an accurate positioning of the fiber relative to the laser beam, both ends of the fiber are mounted on XYZ-stages. The laser system allows for switching between two operating modes (cw and Q-switched) by introducing an acousto-optic modulator (AOM) in the cavity. In one end of the cavity, the fiber facet is angle-cleaved and the output is collimated using an 11 mm focal length aspherical lens (not shown) and directed through the AOM to be fed back by the high reflective mirror (Mirror 3). A further mirror (Mirror 2) is used to reject the remaining pump light. The opposite fiber facet is flat-cleaved and the feedback from the Fresnel reflection serves as the output coupler. The output beam is transmitted through Mirror 1, and collimated with an aplanatic lens (Lens 3) onto the processing lens.

All polymers under investigation were natural and non-pigmented materials. The sample thickness was $d=1.6$ mm for all materials. For the butt-welding and transmission welding experiments, the laser radiation was focused directly onto the interface between the parts, and the parts were pressed together (Fig. 2). Appropriate sample holders were constructed to ensure that a constant pressure $\sigma=0.59$ N/mm^2 is applied to the joining parts. Welding experiments were performed at a constant feed of $v=5$ mm/s using a biconvex lens $f=150$ mm as the processing lens. The focused beam size was estimated to $2w_0=0.4$ mm ($1/e^2$). The focus of the laser radiation was located at the depth equal to the half-thickness of the sample arrangement, approximately $\Delta d=0.8$ mm below the top sample surface for butt-welding experiments, and $\Delta d=1.6$ mm for transmission welding experiments. In order to find out the appropriate process parameter windows, melting experiments in bulk materials were performed, and the modifications were analyzed. The laser power was changed in 1 W steps in the range $P=1$–15 W.

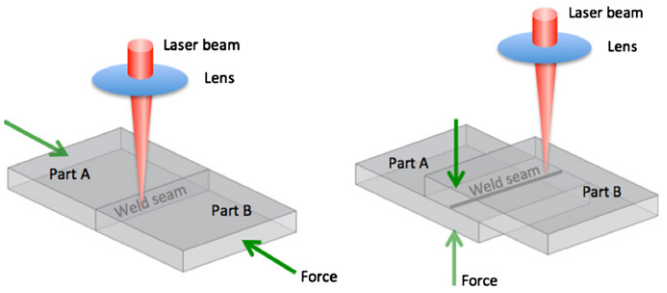

Fig. 2. Experimental arrangements of parts for butt-welding (left) and transmission welding (right).

After irradiation of the samples, the produced melt modifications and weld joints were sectioned across the weld interface using a diamond saw. Then the samples were lapped and polished in a three-step process (Lapmaster 15ATP) to achieve optical surface quality for further characterization.

The spectral properties of all the materials under investigation were studied using a UV–vis–NIR spectrometer (PerkinElmer Lambda 1050). Investigations of melted and welded samples were performed using an optical microscope Olympus BX-51 with differential interference contrast (DIC) capability, and a polarizing microscope Leica DMR XE. Testing of mechanical strength was performed according to the ASTM D638 standard using a tensile tester (Zwick Z100) and the corresponding sample geometries. Mechanical cutting and milling was adopted to bring the samples to a desired shape.

3. Results and discussion

3.1. Spectral properties of polymers

In order to enable efficient laser welding of polymers, the materials must allow a sufficient optical penetration depth. This is important especially for the transmission welding of similar materials. On the other hand, the energy deposition at the weld interface must be large enough to generate a joint melt pool between the joint partners. For the evaluation of the new process windows enabled by the use of Tm-fiber lasers, a basic study of the optical properties of polymer samples with the thickness $d=1.6$ mm was carried out.

Transmission and reflection of the polymer samples were measured in the spectral range $\lambda=0.5$–2.5 μm, and these data were used for the calculation of laser light absorption in this wavelength range (Fig. 3). All the investigated polymers showed a higher absorption around $\lambda=2$ μm compared to the absorption in the wavelength range $\lambda=0.8$–1 μm, where the most common diode and fiber laser systems operate. For example, the materials PMMA and POM reveal about 10 times higher absorption at $\lambda=2$ μm than at $\lambda\approx1$ μm, the operating wavelength of the Nd- and Yb-fiber lasers widely used for polymer welding. This results in a more efficient energy deposition into the material, but also leads to a decreased optical penetration depth in the long-wavelength range.

3.2. Melting experiments

For initial investigation of the light-matter interaction for different polymers, melting experiments were performed. Polymer samples with dimensions $80\times8\times1.6$ mm^3 were processed by focusing laser radiation at the depth $\Delta d=0.8$ mm below the surface and translating the target at a constant speed $v=5$ mm/s perpendicular to the laser beam. Single melt tracks produced

during parameter variation studies, were separated by a distance of 2 mm from each other, and enough time (>1 min) was given for the samples to cool down and re-solidify before applying a new set of process parameters. A constant force was applied to the samples perpendicular to the melt tracks, to ensure a pressure of $\sigma = 0.59$ N/mm^2 at the virtual weld interface. This approach simulates the case of greatest possible proximity of the two joint partners, and delivers a good estimation of the initial process conditions for the subsequent butt-welding experiments (Fig. 2, left).

By changing the laser power in 1 W steps in the range $P = 1$–15 W, an appropriate power range was found for each material. The onset (P_{min}) is identified as the point at which surface and/or bulk modification is first observed with optical microscopy, while the beginning material decomposition combined with generation of soot indicates the maximum power level (P_{max}) applicable for a particular polymer.

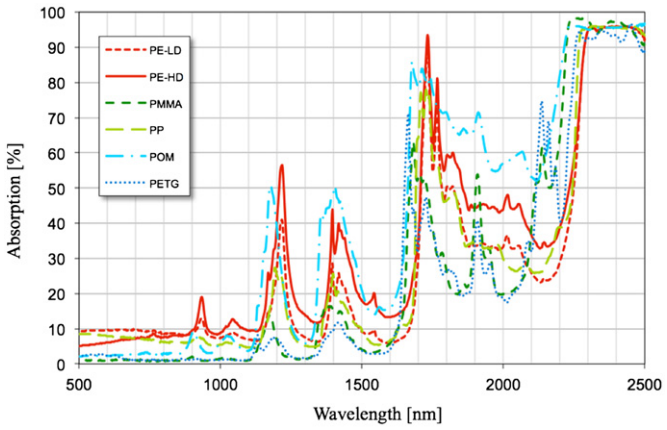

Fig. 3. Absorption spectra of different polymer samples with the thickness $d = 1.6$ mm.

Cross-sections of processed materials PE-LD, PE-HD, PMMA, POM, PETG and PP were prepared and subsequently studied by means of phase-contrast microscopy (Fig. 4). Based on the experimental results, it can be found that an increase of the laser power initially results in an increase of the melt track depth and width until the maximum depth (full sample thickness) and width are attained. Thereafter the track width decreases with increasing laser power, as a result of the reduced viscosity of the molten material. This behavior implies that the entire seam is "soft" over a certain amount of time. Due to the force applied to the sample, the molten material is pressed out of the joining zone. In some materials such as PP and POM, the excessive material is transferred to the surfaces even without a possible movement of the joining partners relative to each other, and a bead is formed after re-solidification. This expansion is due to the volume expansion of laser-molten and re-solidified polymers. The shape of the bead is defined by the re-solidification behavior and viscosity of the material.

The results of the melting experiments were prerequisite for the following butt-welding and transmission welding experiments. In particular, the laser power values P_{min} and P_{max} identified in melting experiments were used for the selection of appropriate process conditions in welding experiments. Additionally the knowledge of achievable melt track geometry was utilized (Fig. 4).

3.3. Butt-welding experiments

Two samples with dimensions $40 \times 8 \times 1.6$ mm^3 were used for direct butt-welding experiments in each trial, and welding was performed along the 8 mm edge with all other process parameters

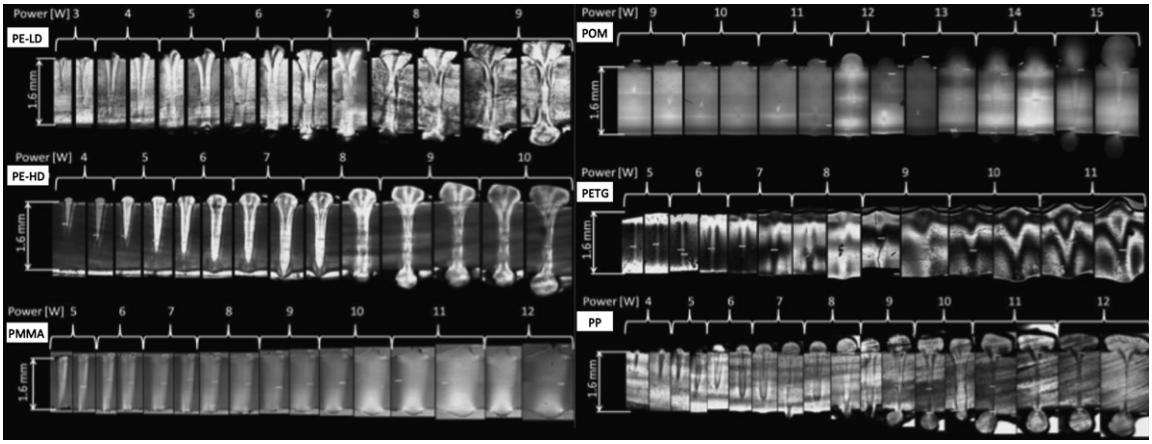

Fig. 4. Cross-sections of polymers processed in melting experiments detected by phase-contrast microscopy.

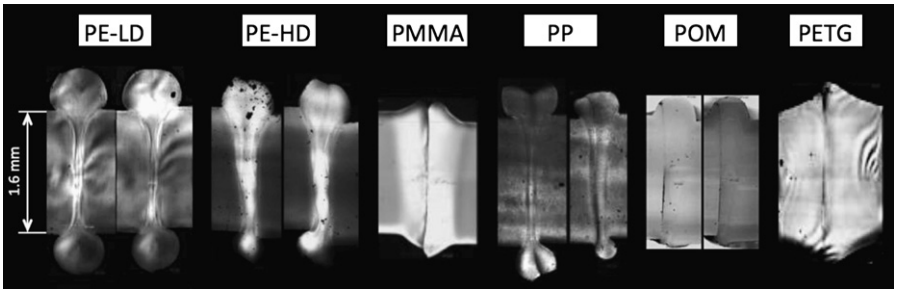

Fig. 5. Examples for cross-sections of butt-welded polymers PE-LD ($P = 8$ W), PE-HD ($P = 10$ W), PMMA ($P = 11$ W), PP ($P = 7$ W), POM ($P = 14$ W), and PETG ($P = 9$ W) detected by phase-contrast microscopy.

set as in the melting experiments. The roughness of the corresponding joining planes was measured before welding and ranged from $R_a = 0.26\,\mu m$ for low-density polyethylene to $R_a = 0.90\,\mu m$ for polypropylene.

The investigations of the cross-sections show differences in dilution behavior of different polymers (Fig. 5). The cross-sections of the welds in PE-LD, PE-HD and PP exhibit well-mixed interface areas without distinct boundaries between the joining partners. In contrary, the interface regions in PMMA, POM and PETG still feature visible edges at any laser power level adopted. Additionally significant variations in the formation of the weld seam and bead can be observed compared to the melting experiments. Partially these variations can be explained by light deflection at the edge defects, and possibly insufficient positioning accuracy.

Furthermore the evaluation of weld cross-sections enables a qualitative analysis of materials' density changes in processed materials. Differential interference contrast microscopy adopted for optical characterization allows a visualization of residual stresses in laser-processed materials, caused by the rapid heating and cooling locally in the interface region (Fig. 5, e.g. PE-LD and PETG). These thermal gradients lead to local expansion, shrinkage and material density changes in and around the laser-processed regions as compared to the non-irradiated material.

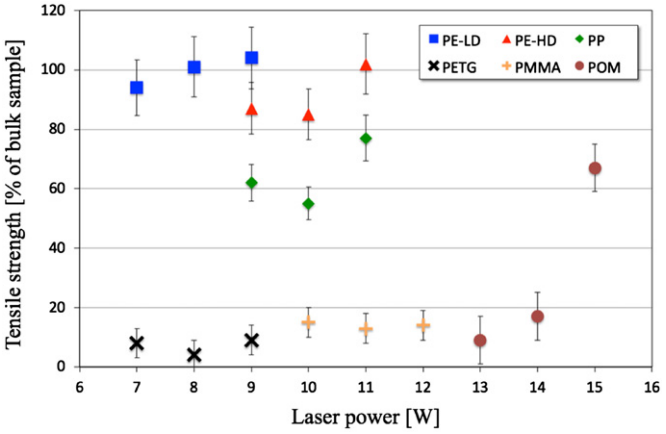

Fig. 6. Tensile strength of laser-welded polymers.

Based on the results of the optical characterization of the weld cross-sections, the set of process parameters utilizable for successful welding was further reduced to three laser power values, and used for preparation of tensile-test samples. These samples were prepared in accordance with the ASTM D638 standard and subsequently cut into two equal parts using a diamond blade saw. After that each pair was laser-welded together using the process parameters determined earlier.

Tensile strength measurements were performed both on intact (bulk) and cut and welded samples to compare the mechanical strength of laser-processed and non-irradiated materials (Fig. 6). The results show that the tensile strength of welded samples of PE-LD and PE-HD is more than 80% of that of the bulk samples. In some tests even a slightly larger tensile strength was measured in welded samples, which is possibly a result of laser-induced chemical changes in polymers, and physical changes e.g. increased joint area due to the constant pressure applied to joining partners. The welded samples of PETG, POM and PMMA revealed less than 18% of the tensile strength of the corresponding bulk material. The analysis of the weld cross-sections for these materials (Fig. 5) indicates that the amount of molten material was insufficient to enable a joint melt pool using the process parameters adopted, and therefore an effective gap bridging between two joining partners. We assume that processing of these materials at lower translation speeds could potentially increase the energy deposition into the materials to support a joint melt pool over a longer period of time, and eventually improve the tensile strength of the welded samples.

3.4. Transmission welding experiments

The transmission welding experiments were performed using the experimental arrangement shown in Fig. 2, right, with four

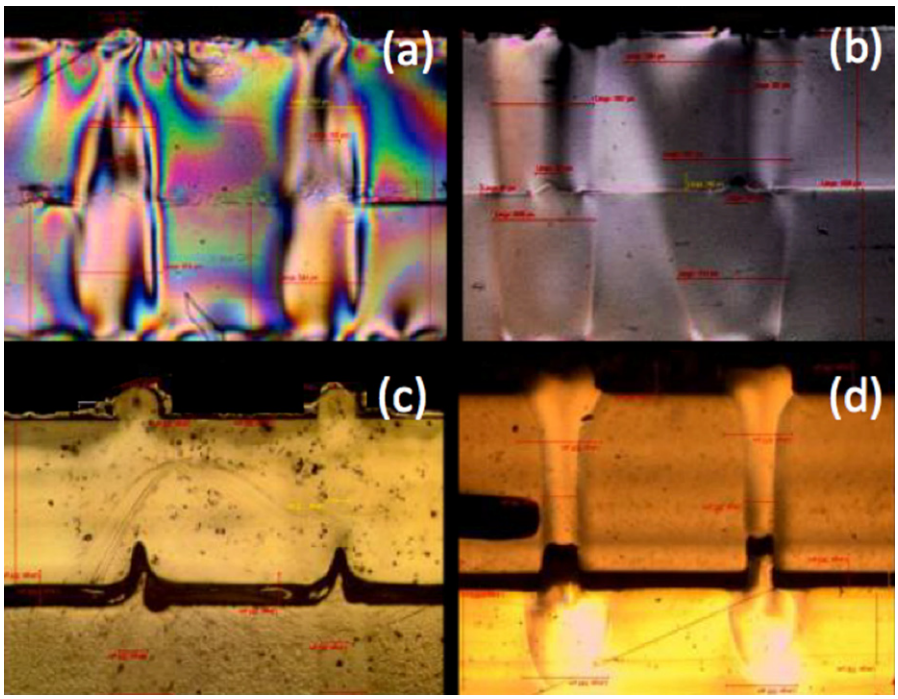

Fig. 7. Examples for cross-sections of transmission-welded polymers: (a) PETG/PETG, (b) PMMA/PMMA, (c) PMMA/PP, and (d) PP/PE-LD, detected by optical and polarizing microscopy. Thickness of all samples is $d = 1.6$ mm.

different polymers in the following combinations (top/bottom material): PETG/PETG, PMMA/PMMA, PMMA/PP, and PP/PE-LD. The same pressure $\sigma = 0.59\ \mathrm{N/mm^2}$ was applied to the joining partners as in the melting and butt-welding experiments, normal to the surface.

The transmission welding of similar polymers PETG/PETG and PMMA/PMMA resulted in a large-area material intermixing in the interface region (Fig. 7). No interface boundaries can be detected in case of PETG/PETG joining. The joining of dissimilar materials PMMA/PP and PP/PE-LD exhibits no effective material intermixing, but the bead produced at the lower, stronger absorbing material penetrates the interface towards the weaker absorbing upper joining partner. Instead of a "material joint", a so-called "form joint" is produced in these material combinations. The maximum material penetration depth was measured at $h = 0.6$ mm for the PP/PE-LD combination. Due to the generation of pronounced form joints, high shear strength is expected as a result of transmission welding of dissimilar polymers.

4. Conclusion

Butt-welding and transmission welding of different polymers and their combinations were performed using laser radiation emitted by a Tm-fiber laser operated at the wavelength $\lambda = 2$ μm. Many polymers reveal considerably higher absorptivity at this wavelength as compared to the spectral range around 1 μm, enabling new process parameter windows for low-energy and eye-safe laser welding without adding any IR-light absorbers. Melting of bulk polymers was first investigated to determine the appropriate process parameters, by utilizing a self-developed Tm-fiber laser system with the maximum power up to $P_{max} = 27$ W. This knowledge was applied to join six different polymers utilizing butt-welding technique. The tensile strength of joined polymers exceeded 80% of the full material strength for low- and high-density polyethylene. Transmission welding was performed with similar and dissimilar polymers and resulted in two different classes of joining, material and form joints, depending on the physical properties of the adopted materials.

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