INVESTIGATION ON THE SUITABILITY OF POLYMERS FOR SELECTIVE LASER SINTERING USING NOVEL MID-IR LASERS

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ABSTRACT

Selective laser sintering (SLS) systems comprise predominantly of 10 μm CO_2 lasers to process polymer powders. However, not all polymers sinter well at this laser wavelength due to their wavelength-dependent absorption properties. Mid-infrared lasers emitting at 2 μm offer an attractive alternative option to process polymers such as polyolefins. This work identified the polymers likely suitable for 2 μm SLS processing through infrared spectroscopy and laser transmission welding experiments. Some of the suitable materials include high-density polyethylene (HDPE), acrylic (PMMA) and the biopolymer polylactic acid (PLA).

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INTRODUCTION

Selective laser sintering (SLS) is a laser-based additive manufacturing (AM) method in which a laser is scanned across successive layers of polymer powder to create a 3D object. The polymer particles coalesce together due to the heating generated from absorption of the infrared laser radiation. This AM technique enables the production of rapid prototyping tools as well as complex actual end-use parts. There is a growing demand to process a greater variety of polymer materials than is currently available in the market, presently limited to a handful of polymer types. It has been reported that polyamides comprise 90%-95% of all laser sintered parts [1]. This dominance is due to the high number of technical constraints that are placed on the material characteristics which must be specially developed for AM processes, and is a major stumbling block towards the progression of SLS technology.

In the SLS systems used to produce polymer parts both commercially and in R&D laboratories, the lasers employed are predominantly CO_2 lasers (λ=10.6μm) [2]. These laser systems are convenient because many polymers exhibit significant absorption around that wavelength. Nevertheless, certain polymers such as polyolefins (e.g. polyethylene and polypropylene) are highly transmissive at 10.6μm, and are not laser processible without the introduction of additives (e.g. carbon black) to modify its absorption behaviour. This constrains the colour choice of polymers available for use in SLS parts. On the other hand, thermally sensitive biopolymers such as polylactic acid (PLA) exhibit such strong absorption at 10.6 μm that attempts at 10.6 μm SLS have been unsuccessful thus far as a result of rapid heating and consequent material degradation. A modified SLS using 1 μm laser was able to process PLA, but it required the incorporation of absorbing additives [3]. Similarly, processing of other polymers using 1μm lasers or other high power near-IR diodes suffer from high optical transmission and absorbing additives are needed to melt the polymers [4].

The advent of 2 μm wavelength lasers offers an attractive alternative in laser processing of polyolefins and several other polymers which exhibit moderate absorption features in the mid-IR region. It can potentially produce higher resolution parts, as well as the printing of additive-free parts, which is particularly important for certain medical applications. By decreasing the processing laser wavelength, the minimum beam diameter can be reduced significantly and consequently, be able to process smaller features by up to 4-fold.

Before SLS process optimisation can take place, the properties of the polymer powder needs to be evaluated first. These include various intrinsic material properties (thermal, rheological and optical) and extrinsic powder properties (powder flowability, distribution, shape) [2].

This work aims to identify, amongst a large variety of polymers, some of the thermoplastic polymers that are processible with 2 μm lasers with a view toward SLS applications.

1. METHODOLOGY

1.1 Materials

A selection of common thermoplastic polymers (PMMA, PC, PP, POM-C, HDPE, PA6), each being 1mm thick, were locally procured for these experiments. PC and PMMA (polycarbonate and acrylic, respectively) are amorphous and transparent, while the others (polypropylene – PP, polyacetyl copolymer – POM-C, high density polyethylene – HDPE, and nylon 6 - PA6) are semicrystalline and semi-transparent to white in colour. Black PMMA and HDPE sheets, doped with absorbing additives, were also obtained. These six polymers were chosen based on their expected absorption around the laser wavelength of the 80 W Tm-doped fibre laser (λ=1940 nm) used for this study. The PLA-based thin film (~50 μm thick) was supplied by CSIR Materials Science & Manufacturing, and is a semicrystalline material. Transmittance in the infrared spectrum was measured using an ABB MB3000 Fourier transform infrared (FTIR) spectrometer.

1.2 Laser system configuration

A continuous wave 1940 nm fibre laser, with output power levels up to 30W, was used to determine the extent of laser-polymer interactions. A scanning system was built and configured to enable sweeping of the laser beam across the polymer strip(s) at a speed of 460mm/min. The beam diameter was 410 μm and remained unchanged across the path of the scanned region. Polymer strips are clamped vertically in a xyz-translation stage and the entire setup is enclosed and purged with dry air.

1.3 Laser-polymer experiments

Laser-polymer interactions were explored in three stages: Firstly, to determine the laser power threshold at which the thermoplastics begin melting. Secondly, attempt to overlap weld clear/neutral to black polymer sheets together using the commonly-used transmission laser welding (LTW) method. Thirdly, perform joining of clear-to-clear polymers via through transmission welding (TTW).

LTW is the traditional method for lap welding of polymers, but this technique restricts the lower polymer layer to be absorbing and dark in colour, while the upper layer must be transparent to the laser beam. These requirements limit the colour combinations in the welding of polymer sheets. Preferential energy deposition takes place at the heat affected zone (HAZ), where melting and diffusion of the material in the interfacial/weld plane occurs and a weld formed. Figure 1 illustrates the principle of LTW.

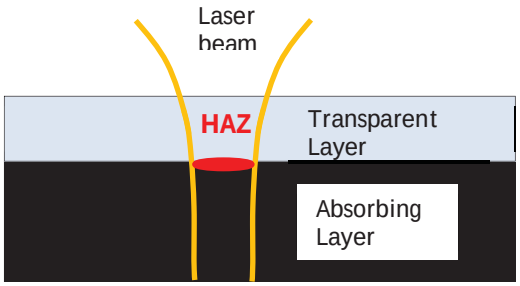

Figure 1 Laser transmission welding of two polymer sheets, comprising a laser-transparent upper layer, and an absorbing lower layer.

On the other hand, 2μm lasers remove such a requirement in TTW, enabling the welding of clear-to-clear and other colour combination polymers. Note that the joining of clear-to-clear polymers cannot be done using conventional CO_2 lasers or near-IR diodes (λ~900nm) without introducing additives.

The quality of the laser welds were inspected by using a Thorlabs Model OCS1300SS swept-source optical coherent tomography (OCT) system, with a lateral resolution of ~20μm.

2. RESULTS AND DISCUSSION

2.1 Laser Absorption by Thermoplastics

Figure 2 shows the measured FTIR transmission spectra for the various thermoplastics sheets and film. Absorption features from the -C=O 2nd overtone and –OH combination vibrational modes are present in the chemical make-up of all the selected polymers and can be observed at wavelengths around ~1.95μm and ~2.1 μm, respectively. The moderate absorption (30 – 83% transmittance around 2 μm) in these polymers implies that they should therefore be laser processible. The decreasing transmittance towards the shorter wavelengths is ascribed to scattering from crystallites present in the semicrystalline polymers (PP, POM-C, HDPE, PA6, PLA), and is not as a result of material absorption. This decrease is not found in the amorphous polymers PC and PMMA.

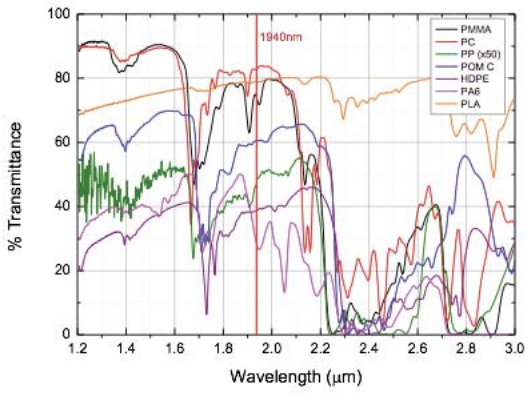

Figure 2 FTIR transmission spectra of 1 mm thick neutral or clear polymer sheets and a PLA film (~50 μm). The scale for PP was magnified by 50× for ease of comparison.

Optical micrographs of some of the neutral or clear polymers exposed to a single laser scan are shown in Figure 2. All of the polymers tested had melted under laser radiation. The thickness of the melt tracks depended on the laser power, material absorption, the crystallinity of the polymer and its thermal conductivity.

It is evident that natural or clear polymers, containing no additives, can be processed and melted with 2μm lasers. Both of the polyolefins HDPE and PP, not processible by CO_2 lasers and NIR diodes without additives, have shown heat-induced melting upon exposure to the 2μm laser beam at power levels no larger than 30W.

With the exception of PMMA at low power levels (~3.5W), it was also noticed (not shown) that all other laser processed polymers contain raised features, or beading, on the surface along the melt tracks. These features can also be seen in the welding results in the next section.

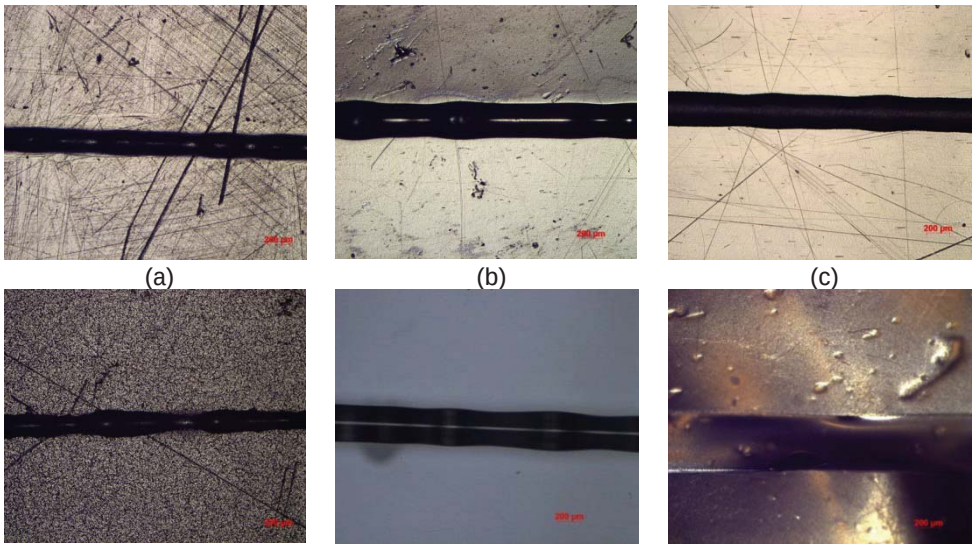

Figure 2 Top view optical micrographs of laser-melted tracks on (a) HDPE, (b) PA6, (c) POM-C, (d) PP, (e) PMMA, and (f) welded PLA films.

2.2 Laser Welding of Thermoplastics

Two of the polymers were further selected as examples, one semicrystalline (HDPE) and another amorphous (PMMA), to affirm their processibility with 2 μm lasers. Two different forms of lap welds (LTW and TTW) were successfully used to join two 1mm thick HDPE sheets, as well as two 1mm thick PMMA sheets together. Cross-sectional images of these laser welds, collected using the non-destructive OCT imaging technique, are shown in Figure 3.

At the interface between the laser transmission welded (LTW) neutral-on-black HDPE, in the red circled region there are faintly visible boundary lines between them, implying little change in the refractive index and no air-gap. There was a small round white feature in the centre, however, which is indicative of some splash back and non-uniform mixing between the neutral and black layers in the HAZ due to excessive heat.

In contrast, for the clear-on-clear TTW of HDPE and PMMA sheets, no splash back can be observed. Much lower energy reached the interface, 1 mm below the surface, due to some absorption by the material of the 2μm laser radiation. There is, however, some splash back on the surface, due to the higher incident laser energy and rapid absorption. The melted surface expands quickly and then cools down, resulting in bead formation [5].

It is seen that conventional LTW using 2um lasers was already achieved at very low power levels of 3.5W for both semicrystalline HDPE and amorphous PMMA. Weld thicknesses of ~780μm and 400 μm for LTW of HDPE and PMMA, respectively was measured. For TTW, the weld thicknesses were 260μm and 390μm For TTW of HDPE and PMMA, respectively.

The HDPE weld seam is smaller than PMMA at the same laser input power because of crystallite scattering experienced in the semicrystalline material; hence less energy is transmitted through to the interface. In SLS processing, HDPE will need higher laser power to process compared to PMMA.

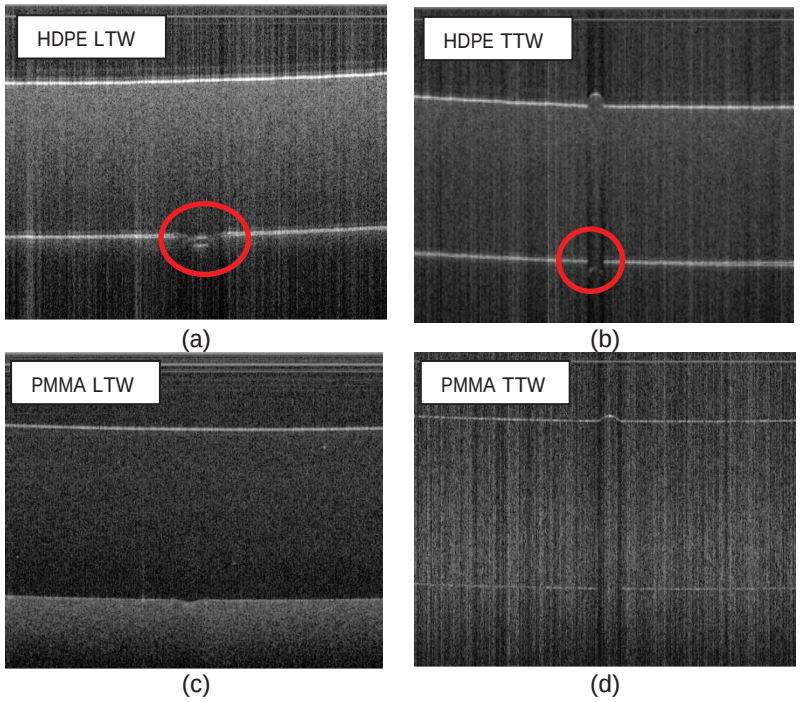

Figure 3 Cross-sectional OCT images of welded 1mm thick polymer sheets (a) HDPE LTW at 3.5W, (b) HDPE TTW AT 8.0W, (c) PMMA LTW at 3.5W, and (d) PMMA TTW at 8.0W.

The PLA films also welded well with a seam width of ~500 μm (see Figure 2(f)), which is slightly larger than the laser beam width but with no apparent visible material degradation. PLA has a number of potential biomedical applications including tissue engineering. Using SLS will achieve a far higher resolution that is not possible with existing FDM technology.

For the fabrication of SLS parts within reasonable timeframes, the scan speed needs to be much higher than the current welding setup and linked to that, an increase in laser power.

The successful welding of HDPE, PMMA and PLA sheets and films are a good indication that particles (of average ~50μm in size) produced from these materials can be melted and subsequently sintered together with very little difficulty.

It also demonstrates that transparent and white polymers (HDPE, PMMA and PLA), unlike in 1μm SLS systems, can also be laser processed using 2μm lasers and therefore for 2μm SLS. Thus far, the only commercial SLS powder available for 1μm SLS systems is a grey-black nylon powder [6]. Furthermore, polyolefins such as HDPE, not processible using CO_2–based SLS systems without incorporating additives, was shown to be possible at 2μm.

3. CONCLUSIONS

A number of thermoplastic polymers were experimentally verified to be processible with 2 μm lasers. Successful laser welds were demonstrated on amongst others white or transparent HDPE, PMMA sheets and PLA films. These imply favourable melting and sintering characteristics for 2 μm SLS systems. Further polymer characterisation, including DSC and TGA, will assist in determining the process parameter space to be used for SLS.

SLS using 2μm lasers should find favour over NIR diodes and 10μm lasers as they are considered “eye-safe”, in addition to being able to process transparent polymers without any additives.

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