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# Manufacturing low-cost fluidic and heat transfer devices by selective transmission laser welding

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**Abstract**

Laser cutting and selective transmission laser welding are combined in a manufacturing process to fabricate flexible, lightweight and inexpensive mini- and micro-fluidic devices using thermoplastic materials such as polypropylene, with applications in fluids engineering, chemistry, bio-engineering, medicine, heat management, and energy conversion. Flexible and lightweight mini- or micro-fluidic devices are advantageous for space, aircraft and portable electronic applications where the device weight and mechanical flexibility are critical design requirements. The fabrication concept is to sandwich an arbitrarily shaped channel, which is cut into a polypropylene sheet, between two transparent polypropylene sheets, which are bonded on the two sides of the cut out sheet by selective transmission laser welding. The proposed manufacturing process was used to fabricate fluidic devices with different applications, including composite thermoplastic materials with enhanced thermal conductivity, continuous flow liquid-liquid mixers, and low-cost transparent mini-channels of arbitrary shape for research purposes.



*Keywords:* Selective transmission laser welding; Microfluidic devices; Laser cutting; Thermoplastic Materials.

## 1. Introduction

Fluidic devices, i.e., devices using one or more fluid streams to perform a certain task, are ubiquitous in industrial applications as well as in everyday life. Depending on the typical sizes of the fluid-carrying channels, one can distinguish mini-fluidics, characterized by hydraulic diameters smaller than 1 cm, and micro-fluidics, where the typical hydraulic diameter is smaller than 1 mm. The ability to control fluids in such small-scale channels led to significant technology innovations in biology (Beebe et al., 2002), chemistry (Ohno et al., 2008), medicine (Polla, 2001), engineering, physical sciences, heat management (Chan et al., 2015), energy generation (Clement and Wang, 2013) and display technologies (Hayes and Feenstra, 2003).

To date, there are several manufacturing approaches to fabricate fluidic and heat transfer devices, including mask-based photolithography, soft lithography, wet and dry etching, 3D-printing and hot embossing (Leester-Schädel et al., 2016). However, these manufacturing methods are labour intensive, and require specialised fabrication facilities such as clean rooms, as well as state of the art equipment. The process is also time consuming, taking approximately 24 hours to fabricate simple devices with multiple design iterations, which increases the cost significantly. In addition, multi-layer devices are even more complicated and can take several days to create because each layer requires its own mold and photomask. As for 3D-printing, the resolution is often limited, which introduces constraints on the channel size and roughness.

Over the past two decades, different materials were used to produce fluidic and heat transfer devices. Typical materials range from monocrystalline silicon and glass to metals to soft polymers such as epoxy resins and polydimethylsiloxane (PDMS) (Lei, 2014). Besides the usual mechanical and thermophysical properties, the material selection should consider features such as mechanical flexibility, air permeability, electrical conductivity, non-specific adsorption, solvent compatibility, optical transparency and biocompatibility.

Certain characteristics of state-of-the-art mini and micro fluidic and heat transfer devices, such as their mechanical rigidity, their weight, and their cost, often make their use technically and economically challenging,

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preventing potential applications to a range of novel consumer technologies, where mechanical flexibility, weight and cost include critical design and/or marketing constraints. For example, flexible fluidic and heat transfer devices would be advantageous in multiple possible configurations where one side is out of the plane with the others, allowing operation in oscillating or deformable systems.

The present work describes a manufacturing process to fabricate flexible, lightweight, low-cost mini- and micro-fluidic devices, overcoming the above issues. In particular, the basic concept is to sandwich a black polypropylene sheet, where a channel (or a channel network) with the desired size, length and shape has been previously cut out, between two transparent polypropylene sheets, bonded by selective transmission laser welding. Laser transmission welding has been successfully used since the 1980s, with applications, among others, in the automotive, electronic, medical and construction industries, and in manufacturing household goods. The use of polymer and/or composite materials for structural components of fluidic devices instead of monocrystalline silicon or glass removes the issues of mechanical strength and ensures adequate resistance to fatigue. In addition, the proposed manufacturing process does not require access to cleanroom facilities, with a significant simplification of the process and a cost reduction.

## 2. Materials and Methods

### *2.1. Material selection*

Thermoplastic polymers are an optimal choice to fabricate versatile fluidic and heat transfer devices. Their advantages in comparison with, e.g., metallic materials, include their mechanical strength to weight ratio, their resistance to corrosion, their mechanical flexibility, the ease of fabrication of a virtually unlimited variety of complex forms and shapes, and their full recyclability. However, their relatively low thermal conductivity and melting temperature may jeopardize their use in heat transfer and thermal management applications.

Suitable polymeric materials to fabricate fluidic devices were selected according to the following criteria: (i) mechanical flexibility: materials with tensile modulus and bending modulus lower than 1 GPa, and elongation at critical stress higher than 2%; (ii) chemical compatibility with a range of different fluids, including water, silicone oils, acid and alkaline solvents, and refrigerants; (iii) maximum continuous service temperature of 120°C; (iv) resistance to abrasion. Based on the above criteria, polypropylene was identified as a suitable material. The channel of the fluidic devices were cut-out into black polypropylene sheets, and then sandwiched between two transparent polypropylene sheets bonded to the black sheet by selective transmission laser welding.

### *2.2. Laser cutting*

A LS1290 PRO $CO_2$ laser cutter with a maximum power of 80 W was used to cut the polypropylene sheets into the shapes required to assemble the various fluidic and heat transfer devices. The cutting quality depends on many parameters such as kerf width, the cut edge roughness, the dross and the width of the heat affected zone (HAZ). However, the most critical parameter is the kerf width, which must be as small as possible.

The cutting parameters were determined by trial and error. In particular, the laser power was maintained equal to 90% of the maximum power (72 W); the cutting head speed was 20 mm/s, and the stand-off distance was 0.5 mm. To improve the cut edge finish, cutting was carried out repeating several engraving passes, removing approximately 0.1 mm of material at each pass. After cutting, abrasive paper was used to improve the finish and remove any debris, dross and dirt from the plastic edge which may affect the weld quality.

### *2.3. Selective transmission laser welding*

In the second step of the manufacturing process, two transparent polypropylene sheets were welded on the two sides of the black polypropylene sheet containing the channel by means of selective transmission laser welding (STLW), as shown schematically in Figure 1a. The polypropylene sheets were welded using a nanosecond pulsed fibre laser (SPI G4 HS-L 20W) with a wavelength of 1064 nm. A Nutfield XLR8-10 scan head and 160 mm FL theta, combined with a pipeline controller plus waverunner software was used to process the samples. The theoretical minimum beam diameter was calculated as $d_{min} = 4M^2\lambda f/\pi D_L$, where $M^2 = 1.83$ is the laser beam quality factor, $\lambda = 1064$ nm is the laser wavelength, f = 160 mm is the focal length of the lens, and $D_L = 8$ mm is the input beam diameter. The spot size $D_z$ was then adjusted by changing the standoff distance using a Thorlabs LTS 150 XY stage, according to:

$$D_z = d_{min}\sqrt{1 + \left(\frac{4M^2\lambda z}{\pi d_{min}}\right)^2} \quad (1)$$

where z is the standoff distance. The polypropylene sheets were irradiated with a spot size of 45 μm and pulse repetition rate of 500 kHz, i.e. the laser was practically run in a continuous wave mode.

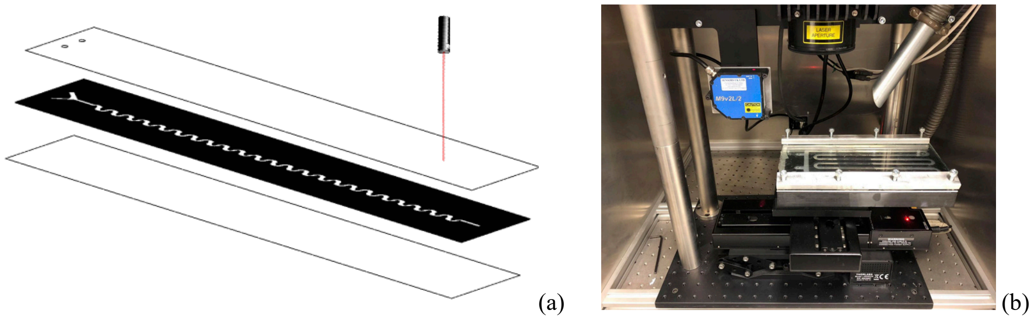

Fig. 1. (a) schematic of the laser welding process; (b) laser equipment with the clamping device.

Optimisation of the laser welding parameters by trial and error resulted into a distance between offset position to the focal position of 2.2 mm, a laser power of 1.9 W and a constant scanning speed of 18 mm/s. The separation between the centerlines of two consecutive scan lines was 40 µm to allow an overlap of 5 µm. To ensure stronger welding and prevent potential leaks, the scan strategy consisted of two passes with orthogonal welding directions. Figure 1b displays the laser welding apparatus with the clamped polymer sheets placed below the scan head.

## 3. Examples of fluidic prototypes

### *3.1. Flexible pulsating heat pipes*

The pulsating heat pipe (PHP) is a thermally driven heat transfer device, which usually consists of a long channel in a serpentine configuration, which is firstly evacuated and then partially filled with a working fluid. Due to capillarity, the working fluid initially resides as an alternation of liquid plugs and vapour slugs. When heat is applied to the evaporator zone, the fluid inside the tube is activated: liquid plugs receive sensible heat while vapour slugs expand due to evaporation and push the heated fluid towards the condenser zone. There, vapour slugs undergo condensation, releasing heat to a cold source. This promotes a pulsating/circulating slug flow pattern along the entire channel length, which significantly increases the equivalent thermal conductance of the system.

A flat polypropylene pulsating heat pipe fabricated by selective transmission laser welding (Der et al., 2019a,b) is displayed in Figure 2a. This device represents an advance in comparison with conventional PHPs, and can be seen as a novel type of composite polymeric material with significantly higher equivalent thermal conductivity in comparison with the raw materials. A set of preliminary test were carried out using FC-72 (density: 1680 kg/m$^3$; surface tension: 10 mN/m) as heat transfer fluid, and a filling ratio of 40%, by heating one end of the PHP (the evaporator), and measuring the temperature difference between the two ends. Figure 2b displays an infra-red image of the adiabatic region between the evaporator and the condenser, showing the active channels of the PHP. The equivalent thermal resistance of the device, defined as $R = \Delta T/Q$ (where $\Delta T$ is the difference between the average temperatures of the evaporator and the condenser, measured at steady-state, and Q is the heat transfer rate at the evaporator), tends to an asymptotic value of about 1.3°C/W, whereas the thermal resistance of the bare composite material of the envelope is around 7.9°C/W. This represents an increase of 585% in terms of the equivalent thermal conductance.

### *3.2. Liquid-liquid mixers*

Dispersions of drops of a liquid into another which is not miscible are common in food, pharmaceutical, personal and health care products, as well as in many industrial formulations; thus, the production of liquid-liquid mixtures with controlled properties has a fundamental importance in many fields of chemical processing. Recently, it was suggested fluid mixing can be enhanced by fluid breakup in chaotic liquid-liquid flows, which can be obtained, for example, by means of secondary flow induced by curved streamlines. Thus, one can build a simple, continuous flow chaotic mixer using a long serpentine channel, which can be easily fabricated with the laser cutting/welding technology described above (Der and Bertola, 2020).

Figure 2c shows two examples of water-in-oil dispersions (flow patterns) obtained injecting the two fluids in the serpentine channel at different flow rates. A continuous flow process is advantageous in comparison with batch processes because it does not have to be interrupted to load/unload the fluid sample. In addition, the optically transparent channel and the comparatively lower velocities enable continuous inspection of the process.

### *3.3. Photocatalytic micro-reactors*

A scalable polypropylene microreactor for photocatalytic studies, fabricated by selective transmission laser welding, is displayed in Figure 2d (Maleki and Bertola, 2019).

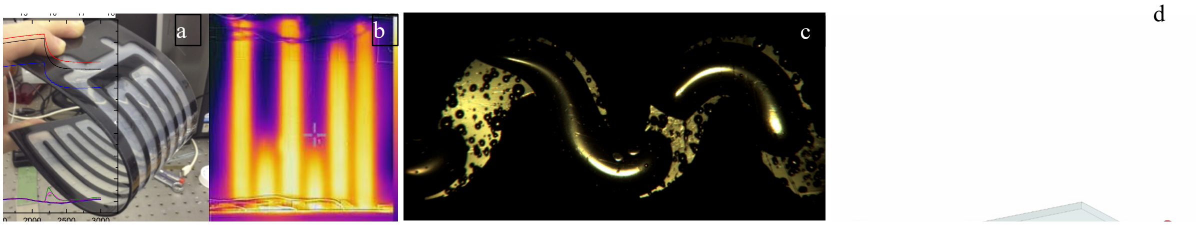


Fig. 2. (a) flat polypropylene pulsating heat pipe; (b) FLIR image of the adiabatic region displaying the active channels; (c) example of water-in-oil slug/dispersed flow pattern observed in the serpentine channel mixer; (d) polypropylene microreactor for photocatalytic studies.

The black polymeric sheet thickness determines the microchannel thickness which in this case was 700 µm. Before the microreactor fabrication, the transparent polypropylene at the bottom was used as a substrate for deposition of $TiO_2$ nanoparticles in a serpentine pattern. The $TiO_2$ deposition was carried out using a modified desktop inkjet printer, and the printing process was continued to obtain a film with a well-defined thickness of the catalyst layer. The photocatalytic tests were conducted in the microreactor at ambient pressure and room temperature. Methylene blue was used for the photodegradation studies with an initial concentration of 4 ppm and UV light as the irradiation source. In this study, the manufacturing procedure and inkjet printing were effective in developing flexible lightweight microreactors and deposition of photoactive $TiO_2$ thin-films.

## 4. Conclusions

An advanced manufacturing process is proposed to fabricate a variety of fluidic devices using polymeric materials. The process consists in cutting out a channel in a black polymer sheet, which is then sandwiched between two transparent sheets of the same material and bonded by selective laser transmission welding. Such fluidic devices are characterised by small thickness, light weight, low cost, and a high mechanical flexibility, which makes them suitable to a large number of emerging applications where fluids and/or thermal management (e.g., cooling) is necessary or desirable, however this cannot be achieved by conventional fluidic devices because of either their mechanical rigidity, or their weight, or their cost.

To demonstrate its potential applications, the proposed manufacturing technology was used to fabricate a heat transfer device based on the pulsating heat pipe concept, a continuous flow liquid-liquid mixer, and a photocatalytic micro-reactor. These examples show the proposed technology represents a promising route to produce a novel class of smart composite polymeric materials with embedded active or passive fluidic and/or heat transfer devices.

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