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Improved manufacturing quality and bonding of laser machined microfluidic systems

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Abstract

Laser micro-machining offers a versatile tool for the rapid manufacturing of polymeric microfluidics systems, with a typical turn-around-time in the order of minutes. However, the chaotic nature of the thermal evaporative ablation process can yield a significant number of defects in the surface of the manufactured microchannels, in the form of residual condensed material. In this work we have investigated the use of solvent evaporation by which to not only laminate bond the laser machined structures but to remove a significant number of the defect formed by the condensation of residual polymer. Results are presented of the surface profiling of the bonded channel structures and demonstrations of the bonding of the microchips to produce autonomous capillary microchannels.

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Keywords: Laser machining, Microfluidics, solvent bonding, defect removal.

1. Introduction

Microfluidics provides a highly versatile platform within which to perform a variety of biological and chemical reactions, with potential in both research based endevour and as commercialized products in applications such as medical and environmental analysis. Conventionally, microfluidics are fabricated using a variety of clean room

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based processes, such as photolithography. Unfortunately such techniques are not readily translatable for mass manufacturing and fundamental translation of the technology from the laboratory to the commercial arena. Therefore focus has now shifted to the development of clean room free technologies, the so called rapid prototyping techniques. Promising technologies include, embossing methods [1,2], injection molding [3], micro milling [4] and laser engraving/ablation methodologies [5,6]. Of these techniques laser micro machining is by far one of the most promising techniques given its rapid turnaround time for manufacture (1-3 minutes/chip), low operational costs, mask/cast-less process, agile design processing through interface with conventional graphical software packages and its ability to process a wide variety of substrates low cost substrates (e.g. polymers). Importantly laser micro machining is readily translatable to large scale mass manufacturing as either the primary or preliminary fabrication technique and therefore is likely to see a wide variety of research focus in the near future. Unfortunately, laser machining using CO_2 based systems are notorious for the introduction manufacturing defects and loss of clarity of polymer substrates during fabrication. This occurs as a direct result of the chaotic evaporation and solidification of material as it is removal from the substrate surface by convection forces and the Gaussian power distribution of the laser spot over the areas being processed [7,8]. Consequently, these defects can negatively impact microfluidic capillary flow based structures in lower aspect ratio channels [6] and make engraved microfluidics less suitable for optical based biological/chemical endpoint analysis on-chip due to increased light scattering events [9,10]. If the power of CO_2 based fabrication techniques are to be fully realized for microfluidic and biosensing applications, methods must be developed to removed or reduce the introduced manufacturing defects, thereby maximizing flow reproducibility over a wider range of channel aspect ratios and reducing light scattering to maximize optical endpoint detection sensitivities.

This paper presents a novel developmental technique for the removal of defects by chloroform based solvent reflow following the laser engraving of PMMA polymeric substrates to fabricate microfluidic structures. Simultaneously, the solvent reflow process allow for bonding of the open channels into closed, laminate structures in a single manufacturing phase. We present initial results regarding optimization of solvent and thermal exposure parameters to yield the greatest degree of defect removal, which has been characterised through direct surface profiling. We also present preliminary parameters by which chips can be adequately bonded to avoid leakage. This technique will provide a rapid and low-cost technique by which to manufacture microfluidic structures in PMMA substrates.

2. Materials and Methods

2.1. Fabrication

All of the polymeric microfluidic structures were fabricated using precast PMMA (Resiplex, Australia) using a commercial CO_2 laser engraving/cutting system (Trotec SP500, Australia) in a similar methodology as described previously [8]. Designs for the microfluidics channels were created using Adobe Illustrator and interfaced with the laser using the Trotec manufactures software and a picture of the utilized system can be seen in figure 1. Briefly, the PMMA sheet is placed onto a z-translatable stage and moved into focus with the laser and microchannels are engraved to a particular depth dependent on the operational speed, frequency and power values of the laser in low power mode and bulk material can be cut using similar parameters in the high power mode. In this work the laser system used had a maximum power output of 40W. The power can be further adjusted in the low power mode dependent on the grayscale of a given design, with black corresponding to 100% and white to 0% of the total energy imparted by the laser for a given speed, power and frequency. Figure 1 shows a graph characterising the depth of etch and the relative error for various laser settings used to achieve a desired depth of etch.

In this work microchips were fabricated comprising 3 individual microchannels with entry/exit ports and approximate channel dimensions of 30mm length and a cross-sectional area of 0.3x0.4mm. Each chip took approximately 1-2 minutes to fabricate and channels were found to be highly reproducible with and approximate variations of ±5-10µm in engraved depths and channel widths, from surface profile measurements.

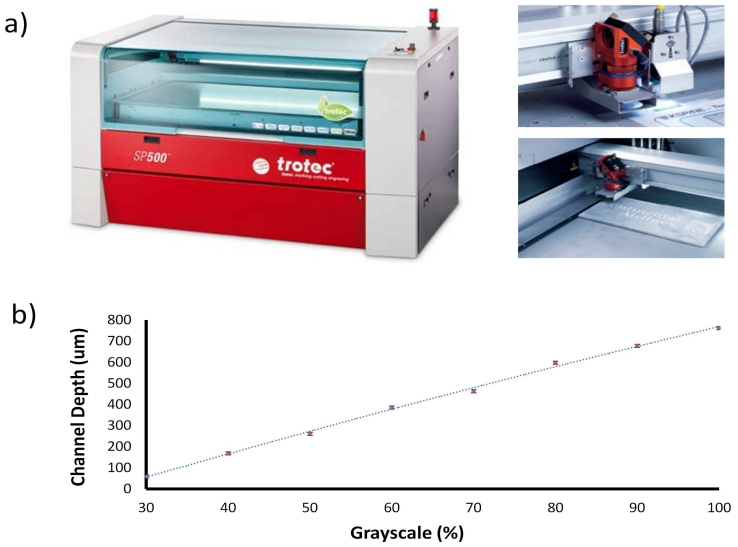

Figure 1: a) A picture of the laser engraving device and b) experimental data relating the depth of engraving in a PMMA bulk substrate for laser setting of speed: 50%, power: 100% and frequency 500Hz, at various grey scales, where 100% corresponds to black.

2.2 Solvent treatment and bonding

Solvent reflow of the laser engraved structures was achieved using a simple solvent evaporation procedure in a similar manner to that described previously [4]. Fabricated chips were initially cleaned using a mild detergent and water, prior to cleaning using a lint free cloth soaked in a 50% methanol solution for no more than 10-20s. Chips were then thoroughly cleaned using D.I water to remove any residual methanol and polymer debris. Chips were then placed with the onto two aluminum pillar placed into a glass Petri dish filled with chloroform solvent, such that the chips were suspended approximately 2-3mm above the upper level of the solvent. Exposure timing began upon placement of the glass Petri dish cover. For thermal processing, solvent exposed chips were placed onto a dry cloth, which was placed upon the active area of a desktop hotplate. Surface profile measurement of the resulting exposed structures was performed using an Infinite Focus surface profiler (Alicona, Australia) to obtain surface images and a Dektak surface profiler (Bruker, Australia) to measure the average roughness of a respective surface. Bonding was achieved in a single fabrication phase alongside solvent reflow by placing the top cover plate onto the aluminum pillars alongside the microfluidic channels. Following exposure the two laminate layers were aligned and pressed together by hand within seconds after removal from the aluminum pillar. The structure was pressed by hand for approximately 30-60s minute and then transferred onto a hotplate and compression applied, after which the compression force was removed and the chip remained on the hotplate for an additional 15 minutes to evaporate away any residual solvents. A schematic of the process can be seen in figure 2.

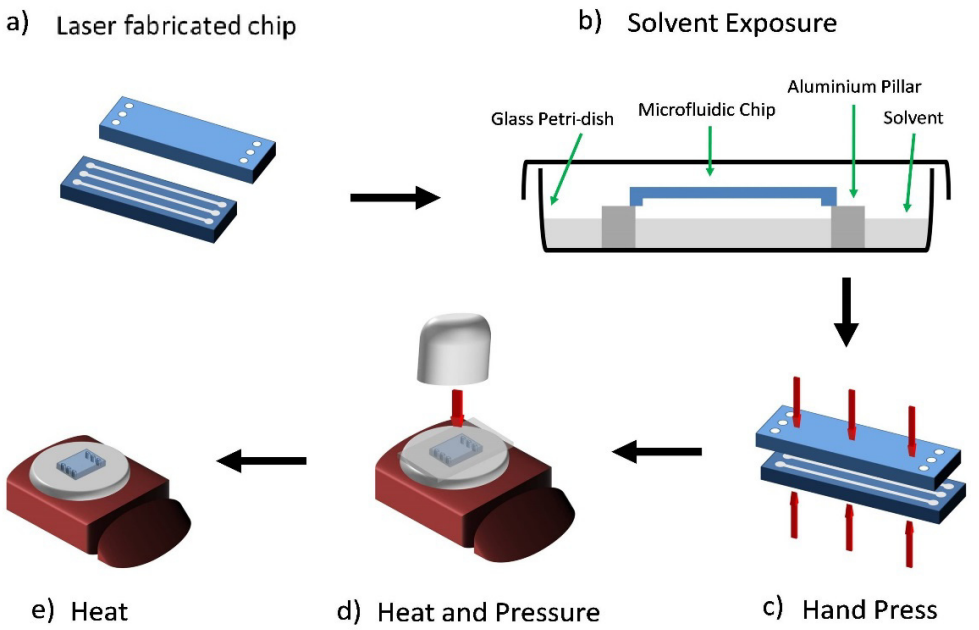

Figure 2: Diagram of the solvent cleaning and bonding process.

3. Results

Tests we performed to expose a laser engraved surface of approximately 400µm depth to chloroform for a time period of 1-9 minutes to ascertain the impact solvent exposure has on the roughness of an engraved surface. Initially untreated, engraved PMMA was exposed to chloroform, but for times of >3 minutes exposure, it was found chips developed cracks on the engraved surface and adjacent bulk material. It was suspected that this was due to the laser engraving process introducing stresses onto the engraved surfaces, which ultimately lead to the fracturing due to solvent reflow. These stressed could be minimized and removed through thermal annealing of the bulk substrate following engraving. Therefore chips were heated to within the glass transition temperature (120oC) and allowed to cool at a rate of 10^{o}C every 30 minutes until a temperature of 50^{o}C was reached, and then allowed to cool ambiently to room temperature. Following thermal annealing, no cracks were observed due to solvent exposure. Figure 3a and 3b show the solvent exposure results, where it can be seen that the roughness can be reduced by approximately a factor of 10 for a 9 minute exposure time relative to the unmodified, engraved surface. It was however found that for such long exposure times the bulk, non-engraved surface began to degrade and loose its clarity. From qualitative evaluation, it was found that an exposure time of 5 minutes provided a good compromise between defect removal in the engraved sections and loss of clarity in the non-engraved bulk material, and so was used as the optimal exposure time.

Bonding of the chips was examined using the same solvent exposure times for defect removal. It was found that for exposure times of >2 minutes the bulk, native surface of the PMMA chips became ‘sticky’ due to the solvents leading to reflow of the PMMA surface. During solvent exposure for bonding both the chip and cover layer were exposed simultaneously for equal time intervals, prior to hand pressing and further heat and pressure treatment by which to evaporate residual solvents and control merger at the chip interface. During bonding various temperatures (50-90^{o}C), hold durations (5-20 minutes) and pressures (0.5-6 N/cm^{2}) were examined to establish optimal bonding parameters. It was found that chips could be sealed by performing a 5 minute chloroform exposure, followed by hand pressing for 30-60s, heating at 90^{o}C with a pressure of 6N/cm^{2} for 20 minutes, before finally heating the chips with no pressure at 90^{o}C for a further 15 minutes. Following this procedure, the chips were allowed to cool to room temperature before testing. Each of the 3 channels formed in the chips could be loaded by means of capillary action

to test the viability of the bonding. Each channel was loaded with 20μL of green test dye solution and allowed to wick the fluid from the loading port to the exit port. To confirm the repeatability of the technique, tests were performed in triplicate where it was confirmed chips did not leak and efficiently allowed for passive loading of the microfluidic channels. Figure 3d shows one of the test chips, with the three channels loaded with green test dye, had the chips leaked such filling would not have been possible.

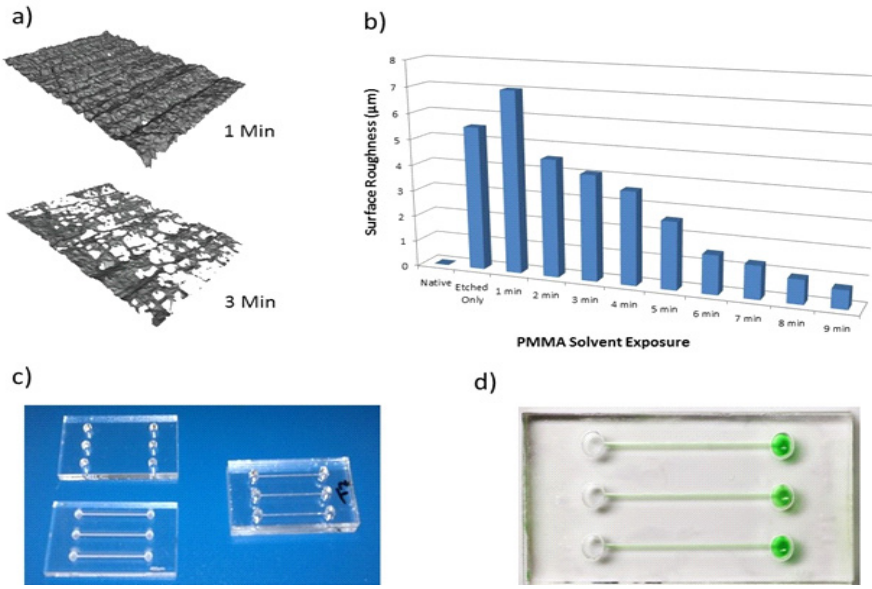

Figure 3: a) Images of surface profiles for solvent exposure times of 1 and 3 minutes. b) A graph of the average surface roughness for various solvent exposure durations. c) A photograph of the 2 chip layers prior to bonding and a fully bonded chip. d) A photograph of a bonded chip loaded with green test dye.

4. Conclusion

This paper presents a novel technique by which to both remove defects and bond microfluidic chips following manufacturing using CO_2 laser based rapid prototyping. The techniques allows for a significantly rapid turnaround time for use as compared to existing clean-room and clean room free manufacturing techniques. We have found the exposure of chloroform in a controlled manner, in conjunction with thermal annealing can reduce defect formation in microfluidic channels by a factor of 10, greatly increasing the potential for this technique as a viable methodology to produce a variety of microfluidic chips for use of capillary systems and alternative microfluidic applications.

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