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A laser microwelding method for assembly of polymer based microfluidic devices

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Abstract

This paper presents the development of a laser microwelding method for assembly and packaging of polymer based microfluidic devices. In this approach a diode laser was used to weld two poly(methyl methacrylate) (PMMA) substrates together at the interface using a thin film metal spot based intermediate layer design as a localized absorber. A broad laser beam with a top-hat profile was used to carry out the laser microwelding work. The effects of laser power and processing time on the resultant heated affected zone (HAZ) and the melted zone were investigated. For large area welding, a 2x2 array of thin film metal spots were used to investigate the effect of separation between the spots on the resultant interfacial bond between the two polymer substrates. For comparison, a large area titanium film with a comparable size to that of the 2x2 array was also studied. The results show that the discrete film pattern based design is better than a single large area film in order to reduce the effect of substrate distortion resulting from the higher temperature rise associated with the latter. The tensile strength of the laser welded joints was determined to be about 6 MPa for a sample produced using the 2x2 array of circular titanium spot pattern design. The laser microwelding method has been demonstrated successfully in leak-free encapsulation of a microfluidic channel.

Keywords
Laser microwelding; Microfluidic devices; Poly(methylmethacrylate); Titanium film; Heat affected zone; Tensile strength

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1. Introduction

Microfluidic devices have found various applications in life science, chemical engineering and many other areas over the past decade. Originally, glass and silicon were used as the main materials for fabrication of these devices due to the available micromachining methods. However, there has been an increasing interest in polymers for microfluidic devices. The advantages of polymers are low cost, chemical inertness, bio-compatibility and light weight. Polymers, such as poly(methyl methacrylate) (PMMA) [1], polydimethylsiloxane (PDMS) [2], SU-8 [3] and polycarbonate (PC) [4], have been used to fabricate microfluidic devices. However, there is still a challenge in sealing and encapsulation of microfluidic devices without damaging or suffering from channel filling problems. Some methods, such as solvent bonding [5, 6], adhesive bonding [7, 8] and surface modification based approaches [9, 10], have been investigated with varying success. However, there are issues with these methods such as low bond strength and structure distortion. Recently localized bonding methods such as ultrasonic welding [11], microwave welding [12], induction welding [13] and laser welding [14] have been investigated for fabrication of microfluidic devices. These methods are suitable for processing of thermoplastic polymers. An ultrasonic welding method has been used to bond PMMA and PEEK (Polyaryletheretherketone) materials for fabrication of microfluidic devices [11]. This work was carried out using a pneumatic standard ultrasonic welding equipment at a generator frequency of 35 kHz. The energy directors and structures were machined into a microchannel chip and a cover plate to guide the melt flow during bonding. In the microwave welding method, two PMMA substrates each with a 100 nm thick gold film were welded together using a microwave source operating at 2.4 GHz [12]. The corresponding power and processing time were 10 W and 120 s respectively. In the induction based welding method a closed loop thin film nickel track was necessary for efficient welding of two PMMA substrates. A film thickness of 7.5 µm was also required to obtain efficient induction heating to bond the substrates [13].

Laser transmission welding methods have been developed for sealing of microfluidic devices due to the advantages of localized heating and therefore minimizing the heat affected zone, fast processing time and good bond strength [14]. This method is a one step process in which heating and welding of the polymer substrates occur concurrently. In this process usually one polymer substrate has high transmittance at the laser wavelength and the other one has high absorptance. The latter absorbs the laser radiation to produce the necessary temperature increase at the interface to cause one or both substrates to melt to produce a resultant bond between the substrates. While this configuration is convenient and does not require additional material for laser welding, it requires a suitable combination of dissimilar materials. Second it is not suitable for fabrication of transparent microfluidic devices since an opaque substrate is necessary to absorb the laser radiation to realize welding of the substrates. On the other hand, transparent microfluidic devices are desirable in many applications that require measurement of optical transmission for medical testing and diagnostics. In the previous work a thin film of carbon layer was used as an intermediate absorbing layer in laser welding of polymer substrates for microfluidic applications [15 -17]. The layer of carbon black was deposited on a microfluidic substrate by spin-coating [15-16] or by vacuum deposition [17] prior to fabrication of the microchannels on the polymer substrate, then a cover substrate is attached to the microfluidic substrate by a laser welding method.
Recently a laser welding method has been used successfully to construct a micropump for lab-on-chip applications using two polycarbonate substrates and a weldable thermoplastic elastomer based intermediate layer [18]. Although it is possible to achieve laser transmission welding of transparent polymers without using additional absorbers at the interface of the two substrates, a fibre laser with a suitable wavelength around 1.7 μm is required and tight control of beam focus at the substrate interface is necessary [19]. The more absorption at the interface due to the focused laser beam (high intensity) at the interface results in a higher temperature increase and thus cause polymer welding at the interface of the substrates. The disadvantage is that a broad beam cannot be used in this method resulting in a narrow welding line with limited bond strength.

In this paper we present a laser microwelding technique for assembly of transparent polymer substrates for fabrication of microfluidic devices. Transparent PMMA substrates are welded together using an intermediate titanium thin film spot pattern and a high power diode laser system with a broad top-hat beam profile. In addition in contrast to the previous work in which the bonding contour is determined by scanning a focused laser beam, in our method the bonding line is defined by a predetermined metal film spot based pattern as a localized absorber thus allowing easy control of laser beam alignment in the bonding process. The dependence of the heat affected zone and weld zone on laser power and processing time has been investigated. The results of tensile measurements show that a strong bond between the substrates can be obtained. Leak free encapsulation of a microchannel device has been obtained successfully using the laser microwelding method.

2. Experimental

2.1 Substrate fabrication
Fig. 1 shows a schematic illustration of the deposition process for producing thin titanium film patterns on PMMA substrates (RS Components, UK) using a shadow mask based approach. The titanium deposition work was carried out using an electron beam based vacuum evaporation system and a PMMA based shadow mask with 1 mm diameter apertures. The mask was fabricated using a CO₂ laser based polymer machining system (Epilog Mini 18, Epilog Laser, USA). The thickness of the PMMA plate for mask fabrication is 0.5 mm. Aperture arrays with separations of 0.6, 0.8, 1.0 and 1.2 mm were fabricated to determine the optimum value for continuous joining between the substrates using discrete titanium film patterns. Before film deposition the PMMA substrates were cleaned in Decon 90 in an ultrasonic bath and then dried in an oven. In order to investigate the effect of film thickness on laser welding of the PMMA substrates, titanium films of thicknesses of approximately 500 nm and 1 μm were deposited on the PMMA substrates. The titanium films were deposited using electron beam based thermal evaporation. The chamber pressure was about 1x10⁻⁶ bar. The beam current and the corresponding deposition rate were 60 mA and 100 nm/min respectively. After film deposition the large PMMA substrates were divided into individual samples for use in the laser microwelding work described in the next section.

2.2 Laser bonding system
A high-power CW diode laser system with a fiber-coupled output at 970 nm (LDM 100, Laserlines, Germany) was used as the laser source in this work. The laser output from the beam delivery fibre was transformed into a large square beam with top-hat intensity distribution [20]. A broad beam allows easy alignment and processing of the substrates in the laser microwelding method. The absorption of the laser beam is determined by the pattern of the thin film titanium spots, the rest of the beam transmits through the PMMA substrates and has negligible effect laser microwelding of polymer substrates. The top-hat beam is desirable for microwelding application since the heat affected zone is small due to the sharp transition of optical intensity in the beam profile and hence the resultant heating effect. The beam profile was produced using a custom-designed beam forming optical element [21]. The beam size is 6x6 mm² and details of the intensity distribution can be found in [20]. Fig. 2 shows a schematic of the experimental setup. The beam transmission module consists of collimation optics followed by a focusing lens with a focal length of 20 cm. The PMMA substrates are placed on an X-Y translation stage. A ceramic plate of thickness of 0.9 mm was placed under the PMMA substrates to improve thermal efficiency as shown in our previous work due to its low thermal conductivity (35 W/mK) as compared to the value of 237 W/mK for the stainless steel platform [20]. Its effect on laser power efficiency is shown in section 3.2. The substrate area with a titanium film is aligned to the laser beam. A glass plate was placed on the PMMA substrate assembly for supporting a metal ring based mechanical load. This is to ensure good contact between the two PMMA substrates during laser welding.

3. Results and Discussion

3.1 Laser microwelding of PMMA substrates

Fig. 3 shows the images of laser welded PMMA substrates showing the area of titanium film, the heat affected zone and the melted zone. The diameter of the titanium film is 1 mm which is much smaller than the size of the laser beam (6x6 mm²). The thickness of the titanium film for Fig. 3(a) is 500 nm and it is 1 µm for the sample in Fig. 3(b). Both samples were produced at a laser power of 25 W and a processing time of 15 s. The processing time is the total amount of exposure time of the substrate assembly to the laser beam. The heat affected zone (HAZ) and melted zone (MZ) are defined to be the zones beyond the perimeter of the circular titanium thin film as illustrated in Fig. 3.

3.2 Analysis of heat affected zone and melted zone

In order to determine the effect of laser welding conditions on the melted (weld) zone and the heat affected zone as shown in Fig. 3, a number of samples were produced and analyzed using an optical microscope (Dino-Lite Pro, Taiwan). Fig. 4 shows the results of the measurements of the melted zone and heat affected zone. Each value represents an average of three independent measurements. As expected both of the melted zone and the heat affected zone increase as the laser power increases. The results are similar for the processing time since the laser induced temperature increases until the steady-state is reached. On the other hand the results indicate that the time to reach steady state of the laser induced thermal effect is longer than 25 s since the width
of the heat affected zone is still increasing until then. The results for processing times beyond 25 s were not obtained since substrate deformation was observed consistently at all of the laser power levels. This is due to the absorption of more laser power resulting in melting of a larger volume of the substrate material and hence causing the subsequent substrate deformation [14]. Comparing the results in Fig. 4(a) and Fig. 4(b), the width of the heated affected zone is about a factor of 10 smaller than that of the melted zone. This is a highly desirable effect for encapsulation of microfluidic devices since the thermal effect on the neighboring region of the functional structures such as microchannels is minimized. Based on the results of optical inspection after bonding for uniform welding contour and minimal substrate deformation, it was found that the suitable conditions for laser microwelding are 25 W for laser power and 15 s for processing time or 30 W for laser power and 10 s for processing time respectively. The improvement in thermal efficiency using the ceramic plate was investigated by comparing the laser power required for the same welding result with and without it. It was found that for the processing time of 15 s, a higher laser power of 28 W was necessary as compared to the value of 25 W using the ceramic plate resulting in a reduction of laser power by about 10% for achieving the same bonding effect.

### 3.3 Studies of separation between two adjacent film spots for continuous substrate bonding

For microfluidic applications it is necessary to produce a closed loop welding line for sealing and encapsulation. In order to study the design parameters of the titanium patterns and in this case it is the separation between two neighbouring titanium spots, laser welding was carried out for substrates with spot separations of 0.6, 0.8, 1.0 and 1.2 mm. The results are shown in Fig. 5. The thickness of the titanium film is 1.0 µm. It was found that this film thickness produces well defined melted zones. Films thicker than 1 µm are also suitable but requiring a longer deposition time. The laser power and processing time are 25 W and 15 s respectively.

It can be seen that for the largest separation of 1.2 mm there is no contact between the two melted zones. But as the separation decreases the two melted zones are joined to produce a continuous line. At the separation of 0.6 mm, the two melted zones merge into one with a seamless transition. The results show that it is possible to produce a well defined continuous welding line using discrete spot based film absorbers. Although a circular spot design was used in this work, other spot geometries can also be used.

Large area joining has also been studied, this work was carried out using samples with 2x2 arrays of titanium film spots. Large area joining between the substrate surfaces can produce a high bond strength that may be required in applications where a high pressure fluid flow is necessary. The spot separation was 1.0 mm and the titanium film thickness was 1.0 µm. The laser power was 25 W and the processing time was 15 s. For comparison of a similar area of welding, a single large square titanium film (3x3 mm²) was used to join two PMMA substrates under identical conditions as for the 2x2 array of circular titanium film spots. Fig. 6 shows the images of the assembled PMMA substrates. Although the total joined area is similar in both designs, there was significant distortion of the top surface of the PMMA substrate that is not shown in Fig. 6(b). This was due to the excessive thermal energy from absorption of the laser radiation by the large titanium film. Therefore the results show the advantage of using an array of titanium film spots for large area substrate joining.
3.4 Cross-sectional studies of weld interface

In order to study the laser welded interface in more detail, the cross-sections of the assembled substrates were obtained and examined under an optical microscope. Fig. 7 shows the images of the cross sections of samples produced at the laser power of 20 W, 25 W and 30 W respectively. The titanium film thickness was 1 µm and the processing time was 15 s. At low laser power, the temperature rise at the interface is just above the glass transition temperature of the PMMA substrate material which was measured to be 132°C on a differential scanning calorimetry instrument (Pyris 1, Perkin Elmer, USA). In this case welding occurs but does not cause breakup of the titanium film. As the laser power is increased to 25 W, the temperature at the center of the film spot region is significantly higher than the glass transition temperature of the PMMA material resulting in melting of a larger volume of the PMMA substrate material as shown in Fig. 7(b). As the laser power is increased further to the value of 30 W, the melting region extends further into each substrate as can be seen in Fig. 7(c). It has been observed that the excessive melting region shown in Fig. 7(c) causes deformation of the substrate surface of the sample. Therefore it is necessary to control the laser processing conditions in order to obtain a reliable bond between the substrates and at the same time not causing substrate deformation.

3.5 Tensile bond strength measurements

Tensile measurements were carried out to determine the interfacial bond strength of the laser weld PMMA substrates. The measurements were made using a commercial tensile strength tester (Instron Series 2715-015, Instron®, USA). Fig. 8(a) shows the schematic configuration of a laser welded PMMA substrate assembly for tensile strength testing. An acrylic circular rod was attached to each PMMA substrate using an epoxy glue (Evo-stik rapid tube, Bostik Limited, England). The two polymer rods were aligned along a straight line to ensure minimal shear stress during tensile testing. The rods were secured to the grippers of the test rig and a tensile load was applied to the sample. The tensile strength for each sample was obtained from the measured load extension characteristic at a pulling speed of 1 mm/min.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Titanium film pattern</th>
<th>Titanium thickness (µm)</th>
<th>Laser power (W)</th>
<th>Processing time (s)</th>
<th>Tensile strength (MPa)</th>
<th>Substrate deformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2x2 array</td>
<td>0.5</td>
<td>25</td>
<td>15</td>
<td>2.88</td>
<td>No</td>
</tr>
<tr>
<td>2</td>
<td>2x2 array</td>
<td>1.0</td>
<td>25</td>
<td>15</td>
<td>5.08</td>
<td>No</td>
</tr>
<tr>
<td>3</td>
<td>2x2 array</td>
<td>1.0</td>
<td>30</td>
<td>15</td>
<td>6.14</td>
<td>Yes</td>
</tr>
<tr>
<td>4</td>
<td>Square film</td>
<td>0.5</td>
<td>25</td>
<td>15</td>
<td>3.18</td>
<td>Yes</td>
</tr>
<tr>
<td>5</td>
<td>Square film</td>
<td>1.0</td>
<td>25</td>
<td>15</td>
<td>4.31</td>
<td>No</td>
</tr>
<tr>
<td>6</td>
<td>Square film</td>
<td>1.0</td>
<td>30</td>
<td>15</td>
<td>4.93</td>
<td>Yes</td>
</tr>
</tbody>
</table>

The results of tensile strength measurements are given in Table 1. A 2x2 array of titanium spot pattern and a single square titanium film were used in the comparative study. The separation
and diameter of the film spots in the 2x2 array design are both 1 mm. The area of the square titanium film is $3 \times 3 \text{ mm}^2$. The processing time and load of 15 s and 4 N respectively were the same for all samples. The total weld area for each sample was measured from the corresponding optical image of the resultant PMMA substrate assembly and used to determine the values of tensile strength shown in Table 1. As can be seen in Table 1, sample 2 has the best tensile strength among the samples without suffering from substrate deformation. For the titanium film of thickness of 1 µm, the tensile strength for the 2x2 array design is better than the large area square film. At the laser power of 30 W, surface deformation was observed for both sample 3 and sample 6. As discussed in Section 3.3 in this case the higher laser power produced a large volume of melting PMMA material from the two substrates causing excessive softening during the welding process and therefore the subsequent surface deformation after cooling. The results also show that the tensile strength is higher for the thicker titanium film. Therefore the film thickness of 1 µm is better for laser welding of PMMA substrates and this is in agreement the results shown in Fig. 5 in order to achieve a well controlled weld zone. Fig. 8(b) shows the picture of one of the two PMMA substrates of sample 3 after tensile testing. Fig. 8(c) shows a similar picture for one of the substrates of sample 6. It was found that a similar amount of titanium film residue was left on each substrate of the samples as shown in Fig. 8.

3.6 Encapsulation of a microfluidic channel

Fig. 9 shows an assembled microfluidic channel using the laser microwelding method described in this paper and an optical picture of the cross-sectional view of the encapsulated channel. The microchannel was fabricated using a CO$_2$ laser based micromachining method [22]. The spot size of the CW laser beam was 75 µm. The laser power was 8 W and the scanning speed was 76 mm/s. The length, width and depth of the resultant channel were 28 mm and 150 µm and 200 µm, respectively. The diameter of the titanium spot was 1 mm and the separation between the adjacent spots was also 1 mm based on the results described in section 3.2. The laser power and bonding time were 25 W and 15 s. The closed loop bonding line was produced by laser microwelding of each section of the bonding interface surrounding the microfluidic structure. After bonding, the laser encapsulated microchannel was tested using a color liquid. The liquid was injected into the inlet reservoir and flew through the channel by capillary effect. Fig. 9(a) shows leak-free operation of the assembled microchannel device, a significant amount of the liquid passed through the microchannel successfully without showing spreading beyond the laser welded bond line. Fig. 9(b) shows a cross-sectional view of the bonding interface, there is no indication of channel deformation after bonding.

4. Conclusions

A new laser microwelding method has been studied for bonding of PMMA substrates using an intermediate metal film spots for fabrication of microfluidic devices for lab-on-chip applications. In this approach the bonding contour is defined by the pattern of the titanium film spots and thus allowing easy alignment with a broad laser beam resulting in a greater process tolerance than the
previous approaches. The thin film spots can also be produced using an inkjet based low cost printing method. The dependence of the weld zone and heat affected zone on laser power and processing time has been investigated. It has been found that a laser power of 25 W corresponding to a beam intensity of about 70 W/cm² is sufficient to produce a good bond at a processing time of 15 s. A continuous weld between the adjacent circular titanium film spots can be achieved by controlling the separation between the film spots. The results on studies of different film patterns show that for large area substrate joining the spot array design is better than a large thin film patch in order to minimize the effect of substrate distortion. Both cross-sectioning and tensile strength measurements have been carried out to study the reliability of the laser weld PMMA substrates. The tensile strength of the laser produced weld is about 6 MPa which is comparable to that of the previous work in laser welding of bulk polyvinyl chloride (PVC) materials [23]. The laser microwelding method has been used successfully in encapsulation of a microchannel device as shown by leak-free operation. The results of the work show a potential application of the laser microwelding method for packaging of future microfluidic devices.

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References


Vitae

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