Lasers in Manufacturing Conference 2019

Laser microwelding and sealing of thin, polymeric lab-on-chips

Ares-Blanco Félix[a*], Otero-Ramudo Nerea[a], Romero-Romero Pablo[a], Guadaño Gonzalo[b], Hein Marko[c], Gründig Bernd[c]

[a]*AIMEN, Polígono Industrial de Cataboi SUR-PPI-2 (Sector 2) Parcela 3, 36418 O Porriño (Pontevedra), Spain*
[b]*LASING SA, C/ Julián Camarillo 26, 1º 7-8, 28037 Madrid, Spain*
[c] *SensLab GmbH, Bautzner Str. 67, 04347 Leipzig, Germany*

Abstract

Transmission laser welding is proposed as an alternative to adhesive bonding for joining thin foils in polymer Lab-on-a-Chip manufacturing. A 532 nm wavelength continuous wave laser was used, together with an acousto-optic modulator and a galvanometer scan head to modulate and deliver the laser beam to the workpiece. A wide range of parameters was tested to study the influence of the laser modulation (frequency, duty cycle), scan speed and laser power up to 5W on the resulting welding tracks. Under 200 µm thick polycarbonate films were welded with a modulated laser. Continuous, homogeneous welding tracks under 100 µm width were achieved, completing sealing paths for complex microfluidics in seconds. These results prove that laser welding is a high productivity solution for the current problem of joining polymeric films with micrometric accuracy, not possible with nowadays alternatives based on adhesive bonding.

Keywords: Lab on a chip; Laser welding; microwelding; laser sealing; polymer welding; microfluidics

1. Introduction

Manufacturing of polymer lab-on-a-chip (LOC) products requires the sealing of a micro structured film (microfluidics) with a second film (sensor) by means of adhesive or bonding.

This operation is a critical point for the quality and functionality of the final product (Yuksel Temiz et al, 2014), and demands very precise positioning and alignment. Current accuracy specifications range under 50 µm total error over a distance of 50 mm. This specification limits the production throughput due to time

* Corresponding author. Tel.: +34 986 344 000; fax: +34 986 337 302.
E-mail address: felix.ares@aimen.es

consuming and costly alignment operations, difficulties for automation, and defective parts. Furthermore, conventional bonding methods like adhesives may suffer shrinkage during the curing process, increasing the alignment difficulty.

Laser welding can provide advantages for the miniaturization, flexibility and durability (shelf life) of the microfluidic chip products and is one of the most promising technologies for sealing complex microfluidic LOC arrangements. However, it is a particularly challenging operation. In the case of laser welding, there are several possible sources of problems: variability in the parts, warping, relative positioning, contact, laser parameters (the process window is very narrow), and the difficulty to keep constant processing speed in very fine and complex welding paths.

In addition, for the specific application of microfluidic LOCs, two more issues have to be taken into consideration: the width of the track paths should be as small as the technology allows. Also, the input of laser energy should be kept as low as possible. Considering the geometry of the LOC arrangement, the bio-compounds are deposited very close to the welding tracks. If the heat influx during welding is too high, the temperature increase would cause denaturation of the proteins in the bio-compounds.

In transmission laser welding (process illustrated in Figure 1), the laser radiation goes through an upper, transparent layer and is absorbed at the surface of a lower layer, melting due to the thermal energy and transferring part of the heat back to the upper part, welding them together. For this to happen, it is necessary to ensure good contact between both layers, which is achieved by applying pressure to them.

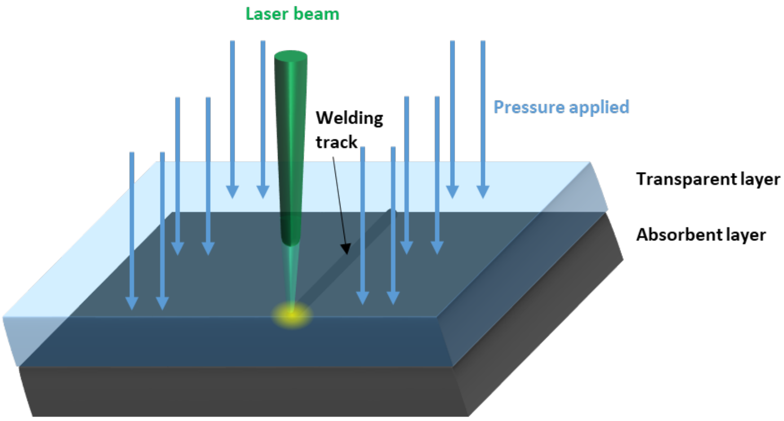

Fig. 1. Transmission laser welding process

2. Experimental setup and procedure

All experiments were performed with a LS-µweld machine developed by LASING S.A., Madrid. The machine integrates a 532 nm wavelength, continuous wave Millennia® eV™ laser source from Spectra-Physics (5 W maximum power and beam quality M^2<1.1), modulated by means of an Acousto-optic modulator and guided by mirrors to a RAYLASE galvanometer scanner head. Furthermore, a machine vision system is installed off-axis to the scanner head for the proper alignment of the foils. This setup is schematized in Figure 2.

The materials used for the experiments were polycarbonate foils. This is a common material used in biomedical devices (Becker, 2002), as it presents good biocompatibility and is highly transparent to visible light when no additive is present. The transparent polycarbonate films were 175 µm thick, while the absorbent polycarbonate films had smoke black additive added to them, in order to increase its absorbance to the 532 nm wavelength laser, and were 125 µm thick.

The procedure is as follows: a transparent polycarbonate film and an absorbent one are placed on a positioner with 4 degrees of freedom, which moves under the machine vision system, places and aligns the foils relative to each other. Afterwards, the aligned foils are transferred into a pressure chamber where compressed air is pumped in, applying pressure onto the foils and guaranteeing good contact between them. The laser is then activated and the foils welded. The pressure of the compressed air is controlled with the LS-µweld pressure valves.

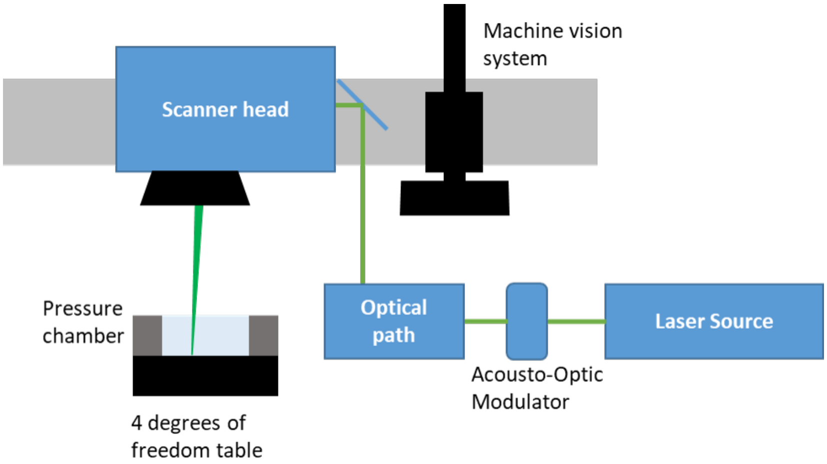

Fig. 2. LS-µweld setup scheme

A wide range of parameters was tested to evaluate their influence in the resulting welding and is shown in Table 1.

Table 1. Range of parameters used in the experiments

Parameter	Value
Laser power	0.5 to 5W
Acousto-optic frequency	CW-100KHz
Duty cycle	30-100%
Scanning speed	10-400mm/s
Pressure	0,5-6bar

For the assessment of the welding quality, we looked for typical defects in the laser transmission welding. The most common defects are failures in seam position, but also defective seams (pores, thermal affection, etc…), and very often, variable seam quality in intricate curvilinear welds. If the welding track results in an incomplete sealing, this will cause the leaking of the microfluidic arrangement, resulting in wrong and non-reproducible measurements. These defects were analysed by means of confocal microscopy. Additionally, we used peel-off and bending testing for the evaluation of the welding resistance. Different geometries were tested, as well as the influence of multiple welding seams parallel or concentric to each other, with various separation distances.

Finally, it is known that the materials surface roughness can highly affect the result of laser transmission welding (Van de Ven, 2007). Therefore, we performed welding tests on flat, smooth samples and on samples with their surface roughness altered. We altered the foils roughness by embossing a microfluidic circuit using two different tools: polished embossing tools and unpolished ones. We chose this method since it is a common process for imprinting microfluidic circuits on polymer materials, hence it allows us to evaluate the welding generated in a real case scenario.

3. Results and discussion

3.1. Welding quality analysis

The firsts experiments performed aimed at narrowing down the parameter window that could provide a satisfactory welding. The influence of the parameters on the resulting welding seam width was observed and tabulated. Table 2 shows the relation between the track width of the resulting welding seam with the laser power and scanning speed, for a fixed value of the other parameters: 100 KHz, 50% duty cycle and 2 bar pressure.

Table 2. Influence of the parameters on the weld seam width

Laser power (W)	Scanning speed (mm/s)	Track Width
0,8	25	105
0,8	50	70
0,8	75	55
1,2	100	55
1,2	200	45
3	100	105
3	200	70
3	300	50

Welding seams of less than 100 µm width were analysed, Figure 3 shows some of those seams that present one or more welding defects. All the experiments shown in Figure 3 were performed with a pressure of 2bar, frequency at 100KHZ and 50% duty cycle, while the laser power and scanning speed were varied: a) 0,8 W laser power and 75 mm/s scanning speed; b) 0,8 laser power and 25 mm/s scanning speed; c) 3 W laser power and 100 mm/s scanning speed.

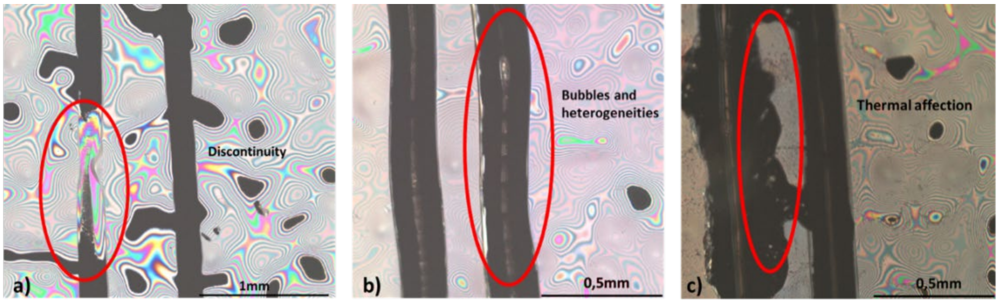

Fig. 3. (a) Welding seam discontinuity; (b) Heterogeneities along a welding track; (c) Thermal affection and material degradation along a welding track

In Figure 3 a) we generated a welding seam of 50 to 55 µm width. Every time we tried to generate welding seams under 60 µm width, discontinuities appear, no matter what parameters we used. In Figure 3 b) we generated a welding seam of 100 to 105 µm width. The bubbles and heterogeneities present along the seam are an indicative that the linear energy deposition is too high, and increasing it would lead us to the defect shown in Figure 3 c), where we generated a welding seam of 95 to 105 width. It should be highlighted that, although it is possible to generate welding seams of similar width by using different combinations of laser power and scanning speed, when using larger laser output power thermal affection is more likely to occur, affecting the material properties and weakening the resulting welding.

Finally, variable seam quality in complex geometries and curvilinear weld was more commonly observed in continuous wave and low frequency processes. Modulating the beam at 100 KHz and setting a duty cycle between 50% and 70% widened the parameter window where the resulting welding seams are acceptable.

After assessing the quality of the welding seams, we chose as optimal the following parameters: 0,8 W laser power, 100 mm/s scanning speed, 100 KHz frequency, 60% duty cycle and between 1,5 to 2,5 bar pressure.

3.2. Bending and peel-off testing

After narrowing the parameter window to obtain continuous, homogeneous and under 100 µm width welding seams, we started experiments to assess the welding resistance. These experiments consisted on bending the welded materials until they started separating from each other and peel-off testing of different geometries. These peel-off tests are shown in Figure 4.

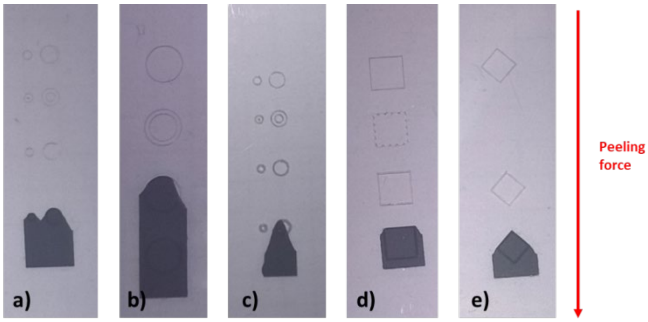

Fig. 4. Peel-off test of different geometries

The welding geometries in all images of Figure 4 were generated with the chosen optimal parameters, with the exception of Figure 4 c), where the laser power used was 1,3 W. The peeling tests were performed by fixating the transparent foil to a flat surface and pulling the black, absorbent foil in the direction of the red arrow.

In images a) to c), the following geometries can be found, from upper to lower row:

- Single circles of different diameters.
- Two concentric circles with 1 mm diameter difference.
- Two concentric circles with 100 µm diameter difference.
- Three concentric circles with 100 µm diameter difference.

While performing the experiments, we noticed that separating the welded geometries of the third row required considerable more strength than the first and second rows. From these three peel-off tests, we concluded that:

- Welding seams parallel or concentric to each other drastically increases the welding strength, up to the point that the 125 µm absorbent foil is teared before the welding breaks.
- Geometries that present more welding surface perpendicular to the peeling force are more resistant those that present smaller welding surfaces.
- Using more laser power and melting more material not necessarily increases the welding resistance

Peel-off tests d) and e) of Figure 4 evaluate the influence of the welding seams orientations respect to the pulling force on the welding resistance. The influence of wobbling and multiple laser passes is also analysed with these two tests. The geometries shown are, from top to bottom:

- Single squares with different orientations.
- Wobbling in sample d), and multiple overlapped passes in e)
- Two concentric squares with 100 µm side difference.
- Three concentric squares with 100 µm side difference.

After these last two peel-off tests, we concluded the following:

- Welding seams perpendicular to the pulling strain present higher resistance, compared with parallel seams which present little to no resistance to tear forces.
- Linear welding seams with 45˚ inclination to the pulling strain present an intermediate, but constant resistance.

Finally, we welded a mock-up circuit to evaluate its behaviour in bending and peel-off tests. The circuit was welded using the optimal parameters selected from previous tests: 0,8 W laser power, 100 mm/s scanning speed, 100 KHz frequency, 60% duty cycle and 2 bar pressure. These parameters generate a welding seam of 80 to 100 µm width. The results of these tests are shown in Figure 5.

Fig. 5. (a) Bending test of mock-up welding circuit; (b) remains on transparent foil after peel-off test of mock-up welded circuit

As it can be seen in Figure 5 a), the welded circuit can be bent a high angle without the foils separating from each other. It must be noted, though, that using thicker foils might provide different results, as they would have higher resistance to being bent.

Figure 5 b) shows the remains of the welded black absorbent foil after being peeled from the transparent one. This is a very positive outcome, as no discontinuities can be appreciated along the welding seams, which means no leakage is likely to occur. There is a small piece of absorbing foil that could not be peeled, due to the circuit design having parallel welding seams very close to each other.

3.3. Roughness influence on the welding quality.

We altered the foils surfaces by embossing a microfluidic circuit on them. Two different embossing tools were used: a polished and an unpolished one. The unpolished embossing tools provided the highest roughness, while the roughness of the foils embossed with the polished tools was closer to the non-processed foils.

Parameters had to be optimized again for the embossed foils, being the most significant change an increase in both laser power and pressure. After optimization, the embossed foils with the microfluidic circuit were welded and the result was evaluated. Figure 6 shows details of a mock-up welding circuit on a) flat foils, b) foils embossed with unpolished tools and c) foils embossed with polished tools.

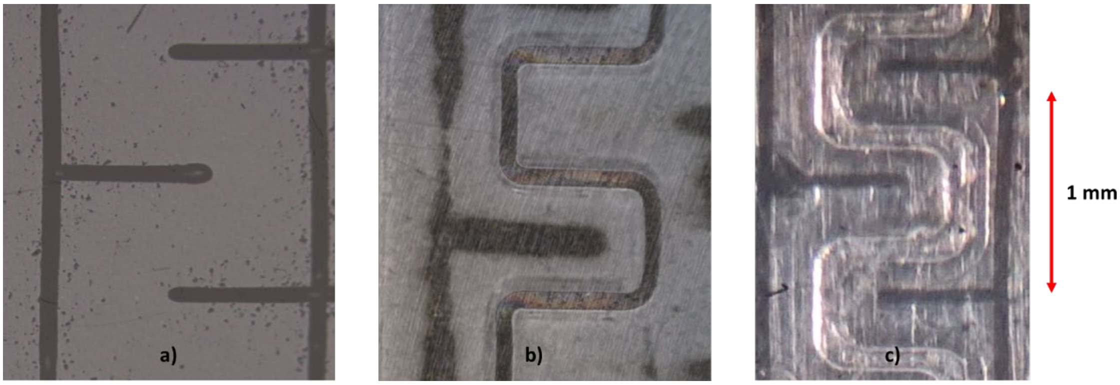

Fig. 6. Comparison between (a) flat foils; (b) foils embossed with unpolished tools; (c) foils embossed with polished tools

As Figure 6 shows, foils embossed with unpolished tools have wider welding tracks, up to 180 µm and they present discontinuities along the welding path. Furthermore, the bonding is weak and thermal affection was spotted, due to the significant increase in laser power required for the welding to occur.

On the other hand, flat foils and foils embossed with polished tools present a similar welding quality and width, less than 80 µm. Along the whole welding path, no discontinuities were spotted in these two cases, and the welding resistance proved to be slightly higher in flat foils.

4. Conclusions

The foils surface roughness plays a critical role in the laser transmission welding process that can render it useless for microfluidic devices sealing. If processes like embossing or moulding are used to imprint the microfluidic circuit, the tools must have been previously polished to sub-micron r_a.

Laser transmission welding is a suitable solution for joining polycarbonate thin foils for microfluidic sensor devices: the welding tracks generated in the process comply with the requirements inherent to polymer lab on a chip manufacturing. Furthermore, the high productivity yield achieved with this technology (the welding process of one microfluidic device can be done under 5 seconds), makes it ideal for mass production.

Acknowledgements

This work was performed within the Lashare Laser Equipment Assessment – PAPS project, which has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 609046.

References

Yuksel Temiz, Robert D. Lovchik, Govind V. Kaigala, Emmanuel Delamarche. (2014). Lab-on-a-chip devices: How to close and plug the lab? - Microelectronic Engineering. Volume 132, 25 January 2015, Pages 156-175

D. Van de Ven, James & G. Erdman, Arthur. (2007). Laser Transmission Welding of Thermoplastics—Part II: Experimental Model Validation. Journal of Manufacturing Science and Engineering-transactions of The Asme - J MANUF SCI ENG. 129. 10.1115/1.2752832.

Holger Becker, Laurie E. Locascio (2002). Polymer microfluidic devices - Talanta 56 (2002) 267–287