DIODE LASER BONDING OF PLANAR MICROFLUIDIC DEVICES, BIOMEMS, DIAGNOSTIC CHIPS & MICROARRAYS

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Abstract

The assembly of plastic microfluidic devices, MOEMS and microarrays requiring high positioning and welding accuracy in the micrometer range, has been successfully achieved using a new technology based on laser transmission welding combined with a photolithographic mask technique. This paper reviews a laser assembly platform for the joining of microfluidic plastic parts with its main related process characteristics and its potential for low-cost and high volume manufacturing. The system consists of a of diode laser with a mask and an automated alignment function to generate micro welding seams with freely definable geometries. A fully automated mask alignment system with a resolution of < 2 µm and a precise, non-contact energy input allows a fast welding of micro structured plastic parts with high reproducibility and excellent welding quality.

Background

The research and development of microfluidic device, so-called lab-on-a-chip technology, is one of the fastest growing areas of medical and biological diagnostics for a variety of applications including DNA analysis, drug discovery and clinical diagnostics [1,2]. Up to now, the preferred materials have been silicon, glass or quartz, mainly because micro fabrication methods for these materials have been extensively developed in the microelectronics industry. However, for many applications, these materials, and associated fabrication processes, are not cost-effective for commercial production and typically for single-use devices.

Plastics are playing an important and ever-increasing role in microtechnology - especially in low-cost, mass-produced applications. It is relatively easy to produce micro structure on the plastic substrates with complex patterns of 50-100µm-sized channels using state-of-the-art replication techniques such as injection molding, hot embossing [3] and UV molding. These substrates are typically used to produce devices on which reactions and high-efficiency electrophoretic separations of biomolecules have been achieved in timescales of seconds to minutes.

Plastics like polymethylmethacrylate (PMMA), polycarbonate (PC) and Cyclopolyolefinpolymere (COC) have been intensively investigated because of their resistance to certain chemicals and biocompatibility. The complete fabrication approach of such a microfluidic device involves two primary steps: (1) formation of micro channels in a plastic base wafer or layer, and (2) bonding of the base layer with a cover sheet to form closed channels. There are several joining procedures for plastic parts including glue cured by heat or UV light, ultrasonic welding and hot gas welding. However, most of these methods cannot, or can only with great difficulty, be adapted to micro structured plastic parts due to the dispensing problems, the use of additional material with different chemical and surface properties, and the lower precision of energy deposition.

The goal of this research was to develop an assembly technology for micro structured parts made from plastics with the goal of producing single-use fluidic devices at an acceptable cost level. The assembly process and the related equipment presented are based on the laser through transmission welding (TTIr) principle. This report describes a device fabrication process and packaging results.

Mask assisted laser transmission welding

Laser welding of plastics was developed in the 1960's, but not until recently has it become a cost effective technology which offers a wide range of advantages because of the non-contact and localized energy input by laser beam [4]. Laser represents a source of clean, controllable, and concentrated thermal and photochemical energy. Due to the recent progress in semiconductor laser technology, compact, economical and reliable laser sources in the NIR range (700 to 1500 nm) are now available which promote the direct use for the material processing with desired power and beam quality.

The principle of the TTIr welding process is indicated in Figure 1. The two plastic parts to be joined must have different optical transmission characteristics at the laser wavelength, one must be transparent or translucent and the other absorbent. The energy of the laser light is transmitted through the transparent part with minimal loss and converted into heat in the absorbing part. By applying a clamping pressure, physical contact between the two parts is ensured and the transparent part is heated by thermal conduction. Surface melting under the illumination of laser beam results in the excitation of convective fluxes within the liquid layer. These liquid layers from both welding parts permit the physical mixture within a cavity at the contact interface and the welding is initiated.

When very small and high accuracy welding seams in the form of lines or areas are required, exact local discrimination of the deposited laser energy must be ensured. With the mask technique the shape of welding seams can be controlled with a high resolution [5]. The principle is indicated in Figure 2. A reflective or absorbing mask is placed between the welding part and the laser source, which generates the lateral energy distribution at the welding surface. The mask is illuminated by a diode bar focused to a line which scans over the mask. The precision of the welding process depends both on the quality of the mask and beam quality of the laser. The mask can be exchanged quickly, allowing for great flexibility in production.

Process equipment

All assembly procedures of microfluidic devices described in this paper are performed by the mask welding system illustrated in Figure 3. The basic process equipment consists of a holder for welding parts, a laser source with optics, a mask, and a vision system for mask alignment. High power diode laser with an emission wavelength in the NIR range is used, typically between 808 nm and 980 nm. For a rapid heating and cooling process of plastic, a power in the range of 80-120 W is required.

In the mask welding process, the welding parts are placed underneath a transparent glass sheet with clamping pressure to assure contact of the mating parts. The mask is fixed on a 3-axis stage (X-Y-ϕ) allowing for precise alignment of the mask relative to the parts. The vision system moving between the mask and holder of welding parts, measures the locations of mask and welding part by using a two point measuring principle and well defined position marks selected directly from the micro structures on the welding part. The locating of defined position marks is carried out by using a pattern matching procedure correlating information about the location and orientation of a known object. According to the measured deviation of the positions the mask will be adjusted with an accuracy of 2 μm to the micro structured welding parts. After the adjustment process the distance between mask and welding part will be minimized. The laser welding process is carried out by scanning of laser source over the mask. This work investigated various levels of system integration that may improve the performance of the system for the mass-fabrication of microfluidic device.

Plastic microfluidic device

There are number of diagnostic devices that require micro channels. In determining the manufacturing method of the channel structure and the packaging of the device the dimensional tolerances, material specifications, and costs should be taken into consideration. For example, a device for the injection and pumping of a precise volume of liquid is achieved through a combination of hydrophobic and hydrophilic regions defined inside the micro-channels. Solutions placed at the inlet port are drawn in by capillary action. Once the liquid is positioned at the desired point, definite volume drops of approximately 10~20 nl can be injected using air pressure from the side-channel. A device for such a task usually consists of a solid plastic base on top of which a thin plastic film is bonded. In the top surface of the plastic base are numerous channels through which the fluids will flow during the handling and analysis process. The plastic film forms the top boundary of these channels. Figure 4 shows some typical macro and micro channel structures of polycarbonate (PC) microfluidic parts which are 14 mm × 10 mm in size and 2.5 mm in thickness (Fig. 4a). This sample has an injection channel and reservoir at the ends of the channel. It consists of a base plate and two tow cover sheets on both sides of the base plate. The cover sheets are 1 mm in thickness. The base plate was an injection molded part. The fine structure of the channel has a dimension of only 100 μm.

Common requirements for assembly of the above mentioned micro fluidic device are joining area, gas and liquid tight joints, and resistance to a few bars. Welding the film to the base must not block any channels, and there can be no delaminations between the film and base, which would permit leakage between adjacent channels. The overall cross-sections of the channels must not be changed during the welding process because of their influence on the effect of capillary action and the transport behavior of the fluids. An exact generation of the welding seams is needed.

Results and discussion

Controlling of melt spreading

The concept of mask welding in micrometer range has implications relating to the rapid heating and cooling of plastic during the welding process. The key factors in establishing the desired welding accuracy are not only the quality of mask and beam shape of the laser, which mainly determine the precise heat transfer, but also the speed of heat treatment and response of material due to the melt flow.

In order to achieve an optimum weld quality for small structures, the melt flow was investigated using both of non-structured (flat) and structured (with micro channels) plastic parts. Figure 5 shows selected test welding seams. Welding structures with a minimum size of 100 μm have been achieved. The behavior of melt flow depends strongly on the welding velocity and viscosity of plastic materials with a characteristic speed of extension that depends additionally on the laser-light intensity and illumination time. The control of this flow was achieved via process optimizing (Fig. 6).

The non-structured plastic welding parts were scanned by a laser source with a constant power of 80 W, equipped with a 150 µm slit mask. The width of the non-welded line was measured as a function of scan velocity. A nearly linear behavior is shown within the narrow range. With scan velocities less than 30 mm/s no well definable structure could be measured due to excessive melt beyond the mask area. For scan velocities greater than 50 mm/s no melt fluidic phase was produced by the laser illumination. It was observed that the speed of melt flow is about 2~3 mm/s. In order to achieve an accuracy of welding seams within 5~10 µm, a maximum illumination time of 3.5 ms is required. A scanning procedure with a line focused laser beam and a high energy intensity allows for a short illumination time.

The use of a laser beam to excite the melting fluxes within the liquid layer plays an important and decisive role for the heat transport, which ultimately determines the quality of the weld. Most plastic materials absorb the laser beam in NIR range only on the top surface with a depth of about a few micrometers. The deep penetration of laser energy can be reached by thermal interaction through liquid plastic fluidics. The quick heating and cooling process is of benefit to the restriction of melt spreading but it may result in a very thin effective convection zone which reduces the welding strength. The compromise must be taken by the excessive coverage of mask to reserve enough places for the expansion of plastic melt fluxes because the melt spreading cannot be completely ruled out by process optimization. The typical dimension of the over coverage is about of 10 to 20 µm, which is dependent on the material to be welded and should be integrated during the mask design phase. In addition, high viscosity of liquid plastic is often of benefit to the restriction of melt spreading due to the slower melt flow.

Figure. 7 shows a microstructure assisted mechanism, which makes it possible to control or stop the spreading of the liquid melt. This structure forms a thin air slit next to the illumination area. As soon as the joining area is illuminated with the laser beam, the liquid melt is guided in a controlled manner into this air slit space. The form of this assisted structuring determines the shape of the edge of melt spreading.

Surface deformation and material compatibility

Because the mask welding process is based on a discriminative heating procedure, the difference of temperature on the welding parts will result in residual stresses[6]. Figure 8 shows the welding seam achieved with a slit mask. A waveform structure at the boundary of welding zone is visible. The reason for that is the temperature gradient near the boundary zone, where the plastic is not efficiently heated to melting point due to the cool surrounding. A growth at the absorbing part with height of 250 nm and a sinking of the surface at the same place on the transparent part can be clearly observed. During the laser illumination the material is melted with overpressure within the interface region. Due to this overpressure the melt is expanded horizontally in all possible directions on the contact surface of welding parts and solidifies with this waveform at the boundary zone. Therefore the boundary of the welding zone is very well defined by this melt wave structure and some fine cornered structures are rounded off in the range of 5~10 µm.

In order to minimize the residual stresses in the microfluidic device, the welding parts with similar melting point is desired. In addition, the material properties, such as thermal expansion and surface tension, also play a very important role and should be considered. One of the successful treatments for reduction of such a stress is the temper of welded devices at moderate low temperature, which has been found very suitable for the mass-production of microfluidic devices.

Process and welding quality controlling

Until recently, there is no active method of process control with the use of the mask technique. However, the optical appearance after the welding process via a vision system offers a capability of quality control. Using suitable illumination techniques, some welding defects can be optically viewed because the air-filled gaps such as delaminations, voids and material decomposition due to the overheating have different reflective conditions in comparison with that of good welded area. The degree of reflection from an interface depends on the difference in welding quality between the two materials involved. Even minute miss-matching of the mask can be clearly detected. It should be mentioned that good looked welding sample may also be poorly welded. To avoid such a problem the welding parameter regarding the scan velocity and the laser power should be finely determined according to the tractive-force-test.

Due to the two points measure principle, the vision system for the mask alignment provides additional controlling mechanisms for the deviation of micro structured plastic parts in comparison to the microstructures on the mask. The measured tolerance during the alignment procedure can then generate error information and show influence on the accuracy of mask alignment process.

Conclusions

A microfluidic device with a channel width of 100 μm has been successfully welded and packaged with desired accuracy using TTIr with a masking based system. The specially designed arrangement with automated alignment and system calibration of welding procedures allows for the use of moderate laser power for a very fast heating and cooling process. For a device with an area of 10x10 mm^2 12 sec. is required, though the real welding time takes only 220 ms.

References

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Key words
laser welding, mask technique, microfluidic, polymer

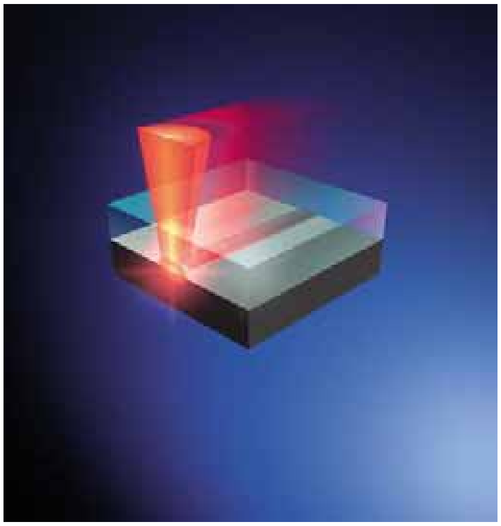

Fig. 1. Principle of laser transmission welding.

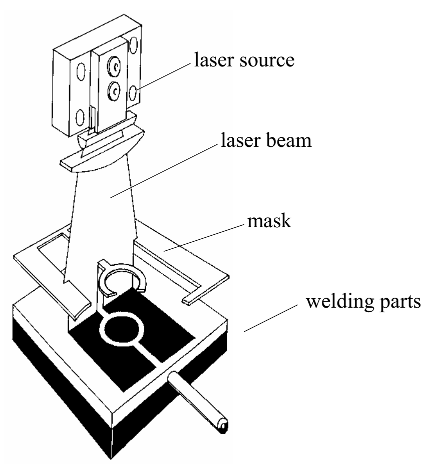

Fig.2. Mask welding. A line focused laser beam is scanned over a mask, which discriminates the energy to the desired weld area.

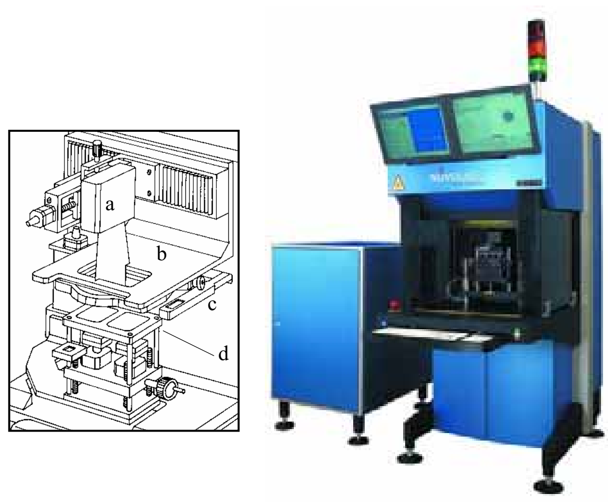

Fig.3. Mask welding system for assembly of plastic microfluidic device. a) laser source, b) micro alignment, c) vision system and d) clamping pressure system.

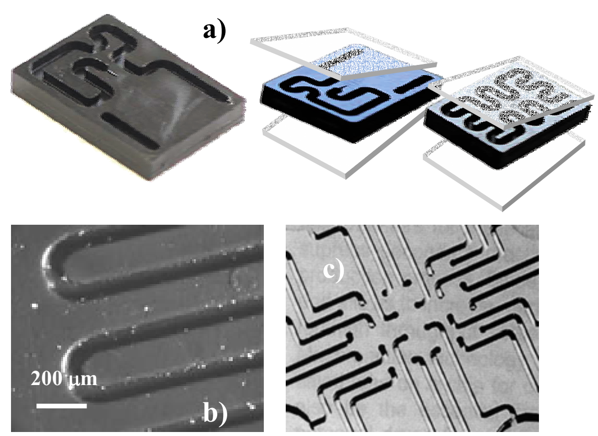

Fig.4. The key component for a microfluidic handling system with macro and micro channels.

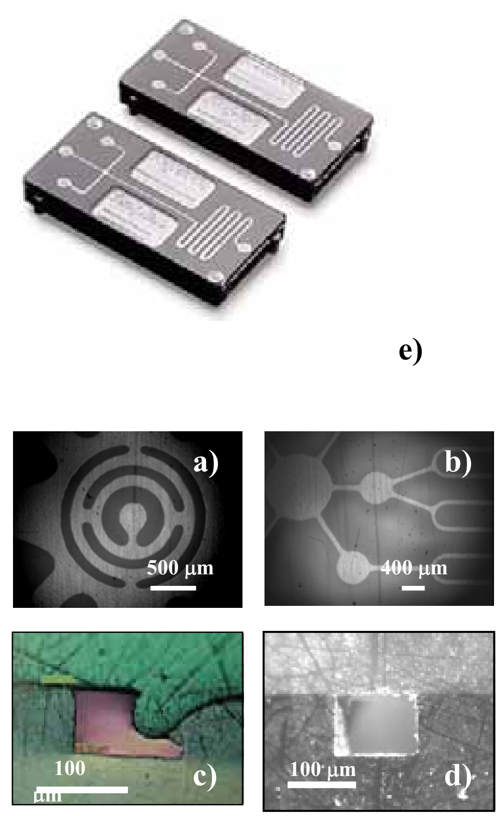

Fig.5. Test welding seams containing various micro structures with different dimensions. a) and b): Welding on non-structured plastic parts, The black areas are welded. c): Micro channels with melt spreading due to the miss-matching of mask. d): Micro channel welded using the excessive coverage of mask. e): Complete welded sample.

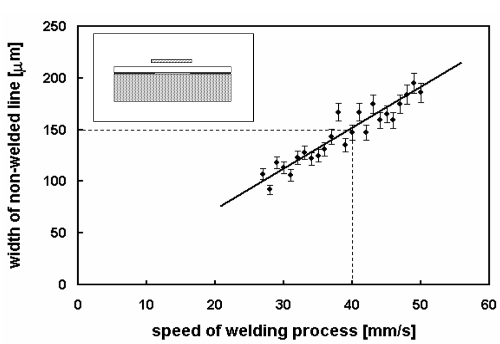

Fig.6. Melt spreading vs. process time

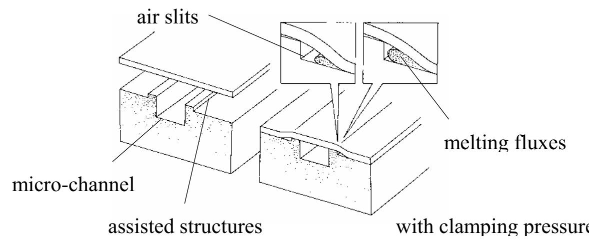

Fig.7. Controlling of melt spreading using assisted micro structures.

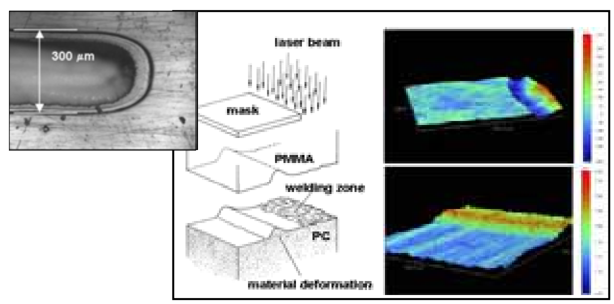

Fig.8. Material deformation on the edge of the welding zone due to the temperature gradient.