DESIGN & DEVELOPMENT OF A MICRO-MIXER-REACTOR FOR A LOC APPLICATION

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Abstract: Miniaturisation has led to development of different micro level systems like microfluidic systems, Lab on Chip (LoC) etc. which have revolutionised the ideas of modern research and development and engineering. In this paper an attempt has been made to setup the design and development guidelines for a micro-mixer or separator chemical reactor and developing a chemical micro-reactor with the set guidelines as a case study. Ultraviolet (UV) cured adhesive bonding technique is experimented, discussed & reported in this paper.

Keywords: Bonding and packaging, Design and development, LoC, Microfluidic devices.

I. INTRODUCTION

Microfluidics is a multidisciplinary field intersecting engineering, physics, chemistry, nanotechnology and biotechnology, with practical applications to the design of systems in which small volumes of fluids will be handled. Microfluidics emerged in the beginning of the 1980s and is used in the development of inkjet print heads, lab-on-a-chip technology, micro-propulsion, and micro-thermal technologies. It deals with the behavior, precise control and manipulation of fluids that are geometrically constrained to a small, typically sub-millimeter scale. A Lab on Chip (LoC) is a microfluidic device that integrates one or several laboratory functions on a single chip which is of size ranging from a few millimeters to a few square centimeters. Integrated system of micro or nano fluidic channels combined with pumps, valves, active micro-fluidic device and sensors is known as Lab on Chip (LoC).

LoCs provide advantages, which are specific to their application. Typical advantages are: Low fluid volumes consumption (less waste, lower reagents costs and less required sample volumes for diagnostics), faster analysis and response times due to short diffusion distances, fast heating, high surface to volume ratios, small heat capacities, better process control because of a faster response of the system (e.g. thermal control for exothermic chemical reactions), compactness of the systems due to integration of much functionality and small volumes, massive parallelization due to compactness, which allows high-throughput analysis, lower fabrication costs, allowing cost-effective disposable chips, fabricated in mass production, safer platform for chemical, radioactive or biological studies because of integration of functionality, smaller fluid volumes and stored energies.

Some major application areas (both bio-medical and chemical) are:

a. Proteomics and Enzymatic Analysis
b. Clinical Pathology and Cell Handling
c. Drug testing or Biomedicine
d. Air, water and earth sampling
e. Micro-reactors
f. Blood and Deoxyribonucleic Acid (DNA) analysis and Polymerase Chain Reaction (PCR)
g. Chemical Process industry

II. OBJECTIVE

1. Setting the design and development guidelines for generation of a micro-mixer or separator LoC using literature and set of experimentation on some micro devices.
2. Design and develop a LoC for a selected process using the guidelines set. Here the process adopted is Ionic liquid synthesis.

III. METHODOLOGY

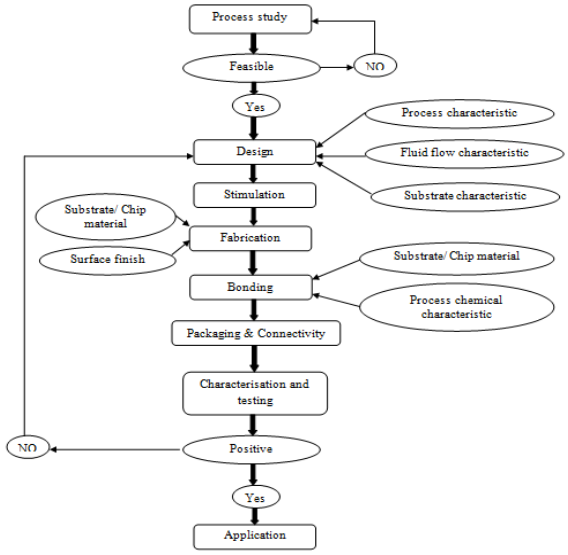

Fig.:Methodology for Design and development of a LoC

IV. DESIGNPARAMETERS

Any LoC is designed by taking into consideration

following parameters: The chemical nature of reaction, the fluid flow characteristics or rheological behavior of the process and the chip material to be used.
The processes considered here are the ones that require complete mixing and diffusion which take hours at a macro level for complete reaction. Processes with solid or precipitates as reactant or end products cannot be used as they will choke up the chip channels. Reactions involving fluids are only considered here.

Chemical process and other process related characteristics:
The type of reactants and products and the type of reaction plays an important role in the design of any chip. The properties of reactant/ product like viscosity, density, wettability, reactive nature etc. define the size and material of a chip. The type of reaction i.e. exothermic or endothermic, type of mixing required and end product derived (chemical nature) also are inputs to design.
Pressure and flow rate also important as increase in flow rate increases the pressure applied in channels. According to these the chip material and bonding processes have to be decided.

Chip Material and channel dimensions:
Material of the chip is decided by the process. If multiple materials can be used then the one having least cost of procuring, manufacturing, bonding and packaging is preferred.
The channel dimensions are set according to the design guidelines. It is preferred that the minimum dimension of the channel be 250x 250 µm.
According to process and process parameters study and substrate properties study the following formulas were developed for chip design (using some literature):
For a microchannel: Laminar flow
Reynolds number: $R_e = \frac{(\rho \times v \times D_h)}{\mu}$
Pressure drop: Navier Stokes equation
$\Delta P = Q \times R$(Straight channel)
$\Delta P = Q \times R + q \times r_s \times \theta$(S-channel- derived)
$R = \frac{(12 \times L \times \mu)}{(w \times h^3)}$ …for rectangular channel (Haigen-Poiseuille equation)
$R = \frac{(8 \times L \times \mu)}{(\pi \times r^4)}$….for cylindrical channel
Length of mixing and reactions:
$L = \frac{(Q \times w)}{(2 \times A \times D)}$ ….for straight channel

where, (all units in SI units)
ΔP = Pressure drop, ρ = density of fluid, μ = viscosity of fluid, Q = volume flow rate, R = Resistance of channel, q = mass flow rate, D = diffusion coefficient of the fluid, V = mean fluid velocity, r_s = s- curve radius, θ = angle of curve, L = length of channel, w = width of rectangular channel, h = height of rectangular channel, r = radius of cylindrical channel, A = area of cross-section of channel = w*h, D_h = hydraulic diameter of the channel.

V. DEVELOPMENT PARAMETERS

Manufacturing techniques:
It is purely dependent on the chip material/substrate, type of channel required (cylindrical or rectangular) and the level of finish to be acquired.
Surface roughness plays very important role in a micro domain as high roughness can cause turbulence and increase the pressure drop. On the other hand it also enables better mixing and heat removal.
Multiple fabrication processes can be used for a single channel but the one which is most economical and gives best results in terms of process requirements in least possible time without requiring any further processing to be done is selected.

Bonding techniques:
A wide range of bonding techniques has been developed to bond glass and other substrates such as metals, plastics, acrylics etc. Some of the techniques being used are thermal bonding, wax bonding, adhesive bonding, anodic fusion etc. In the adhesive technology itself there are different adhesives developed according to the application. Most of the adhesives developed today are synthetic and can be classified as epoxy, polyurethane, acrylic, silicones, cyanoacrylates etc. Other classification is done as application based as 2-part, 1-part, RTV, UV-cured etc.

The bonding of chip to the covering is a very important aspect as if it fails then the whole system will fail. The bonding technique depends on type of chemical used and pressure and temperature of the application.
UV cured adhesives are clear, colorless, liquid photopolymer that will cure when exposed to ultraviolet light. Since it is a one part system and 100% solids, it offers many advantages in bonding and are chemical not reactive to many reagents after curing. The requirement is only glass or plastic which transmits UV light from 350-400nms for different adhesives range.
Norland optical adhesive NOA-61 was considered for further experimentations. The data sheet is as given below:

Adhesive	**NOA 61**
Supplier	Norland Products
Solids	100%
Viscosity at 25°C	300cps
Elongation at failure	38%
Modulus of elasticity (psi)	150,000
Tensile strength (psi)	3,000
Hardness- Shore D	85
Water absorption	0.15%
Refractive Index of cured polymer	1.56
Wavelength for curing	330-380 nm
Comments	Aging required.

Table: Data sheet of NOA-61.

The problems that were to be solved for using the adhesive were: Flow of the adhesive inside the channels as the viscosity is very less and draining of adhesive around channels causing leakage when in

application. Following figures show these trends.

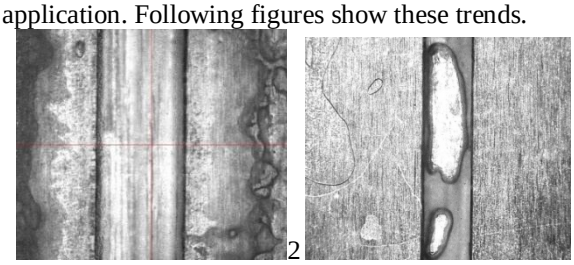

Fig: 1. Adhesive drained out around the channels. 2. Adhesive flown into channels and solidified after curing causing blockage.

To solve these problems several tests were carried out and finally a set of steps was developed for using the adhesive effectively without any of the earlier issues. The procedure is as follows:

a) Apply tape on two end edge sides of the glass or PMMA substrate used for covering.
b) Apply adhesive (NOA-61) on the teflon substrate.
c) Place glass piece on the teflon substrate and apply pressure to evenly distribute the adhesive all around the glass surface.It will also ensure least possible thickness of the adhesive which won't move further except semi-solidification at its initial location.
d) Now do the precuring (semi solidification) of the bond (time depends on source of light used like Mercury vapour lamp or Light-Emitting Diode (LED) light etc.).
e) Remove the glass from the teflon using the tapes.
f) Place the other surface (either PMMA or glass or metal) on the cured adhesive side and apply pressure.Due to least thickness of the adhesive, segregation, aggregation, flowing towards unwanted region (inside the channel) will be mitigated.
g) Cure the bond through the sides using UV source for partial curing under pressure.
h) Remove pressure and then completely cure the adhesive.
i) Keep for ageing to gain complete strength.

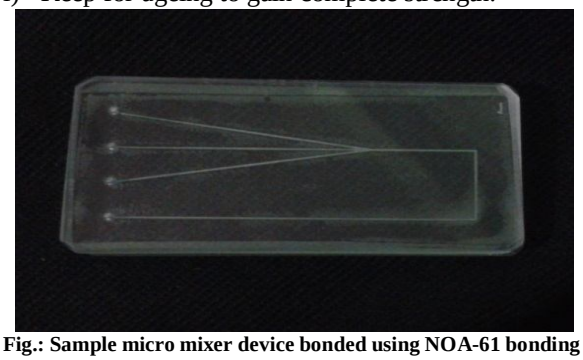

Fig.: Sample micro mixer device bonded using NOA-61 bonding of PMMA (having channels) and glass substrate (for covering).

Packaging Techniques:

Once the chip is fabricated and bonded it is packaged for micro to macro connectivity, structural integrity and aesthetics.

Micro to macro connectivity is one of the most important aspects of any LoC application. Major problems that occur are leakage at the intervals of the connectors, fluid reactive flow to other channels and connector tubes etc.

Packaging is also done to provide structural toughness to the chip. There are several packaging techniques like one having parallel input output connections, perpendicular input output connections and mixed ones.

Also the chip can have integrated packaging to reduce the losses due to leakage and also for aesthetics.

The figure below shows a micro-reactor NOA bonded and packaged with perpendicular connectors for macro (syringe pump) to micro connectivity (chip channels.).

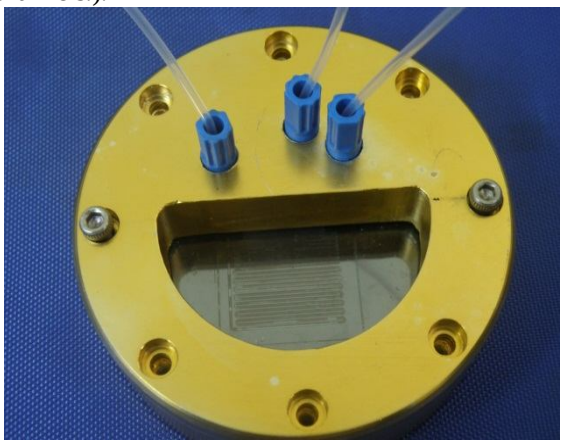

Fig.: Above picture shows a silicon micro-mixer reactor packaged and connected with connectors ready for testing using a syringe pump.

The setup was tested for pressures upto 15 bars using water but there was no delamination of the silicon with glass bond.Although the flow was restricted as the size of the channels was found very less (250µ x 75µ – width x depth) for a length of 750mm due to which there was large pressure drop and hence no flow after certain length of channel. The reactor is also been redesigned for greater depth so that flow happens.But this reactor will be implementable to handle other fluids which have low density & viscosity.

VI. CASE STUDY

Using the set design formulas and guidelines developed from study a device is been designed for the Ionic liquid synthesis process to produce **1-Butyl-3-methylimidazolium bromide** (BMIM-Br). The substrate is considered as PMMA for chip and as cover as it is easy to procure, manufacture and bond using NOA. Mechanical micro milling is considered initially as the process for manufacturing. The design parameters derived are:

For:

ΔP =10 bars to 2 bars= 8 bars, Q = 10 ml/min,

ρ = 1.2 g/cm3, μ = 1.98 x 10-3 kg/ms,

w = 0.5 mm, h = 0.5 mm, r_s = 1.2 mm, θ = 180□

gives,

Length of straight channel, L = 25 m (pure diffusion, pure laminar flow),

Length of s- channel, L = 3 m (mixing plus diffusion, transition flow).

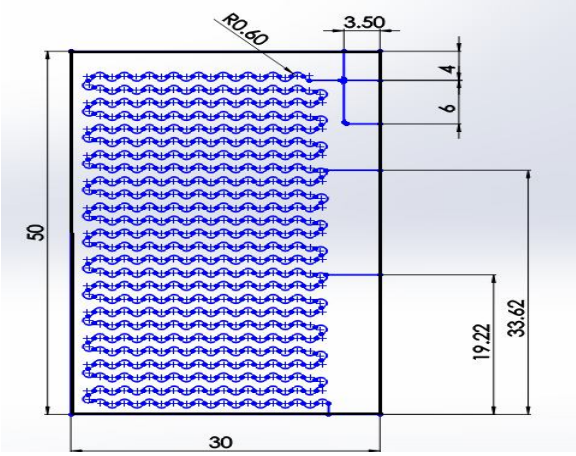

Fig:The designed chip with the s-channels (only tool path).

Since there was size constraints of chip not more than 50mm x 30mm so multiple chips are to be used in series with intermediate pressure intensifier for complete process to be performed. The total channel length in each chip will be 700mm. The chip has 3 input ports and 3 output ports for deriving the product at various length of channel.

According to the given drawing CNC codes was generated using MASTERCAM software which has around 1200 lines as coding for the micro-milling operation.

The codes are fed to DT110 machine (Make: Mikrotool) for milling operation to fabricate the channels having width of 0.5mm and depth of 0.5mm on PMMA sheet of thickness 3.5 mm with a carbide tool.

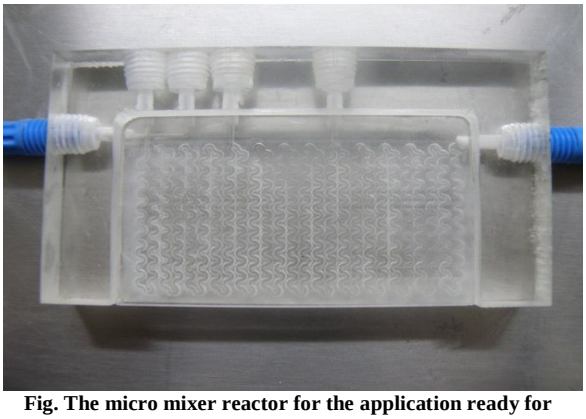

Fig. The micro mixer reactor for the application ready for testing.

The above figure shows the final product developed in PMMA for the reaction according to the design parameters. It is bonded using NOA with a PMMA cover and is enabled with the packaging for the micro-macro connectivity with parallel input output ports. There are 3 inputs for the three reactants and 2 intermittent (at approx.200mm and 475mm) and one final (at 700mm) output for derivation.

Similarly flow and pressure test was carried and it was found to be satisfactory and no leakage or bond failure was found. Further testing is to be done to check for the mixing and reaction processing in the micro device.

CONCLUSION

After various literatures study and experimentation performed on various micro-devices the design and development guidelines were derived, using which a device was manufactured for a particular process. Tests for flow without leakage and pressure were found satisfactory and further testing for mixing and reaction is being carried out.

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