MOLDING AND BONDING OF THERMOPLATIC MICROFLUIDIC DEVICES

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SCHOOL OF MECHANICAL AND AEROSPACE ENGINEERING

2014
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A thesis submitted to the Nanyang Technological University in partial fulfillment of the requirements for the degree of Doctor of Philosophy

2014
Acknowledgements

First and foremost I want to thank my thesis advisor, Associate Professor Tor Shu Beng. It has been an honor for me to be his Ph.D. student. He has taught me, both consciously and unconsciously, how good research is done and how to pursue happiness along with research even during tough times. I appreciate all his contributions of time, advice and funding to make my Ph.D. study challenging and meaningful.

I want to thank my PhD confirmation examiners, for their invaluable suggestions and encouragements. I am also grateful for those constructive discussions with many others, particularly Professor Anand Asundi, Associate Professor Liu Erjia, Dr Fu Gang and Mr Chong Zhuangzhi.

Nanyang Technological University is very generous in supporting me with full scholarship assistance and providing an excellent academic environment for my study and research. I would like to thank the staffs of Manufacturing Process Lab II and NTU Additive Manufacturing Center, Mr Chia Yak Khoong and Mr Wee Tiew Teck Tony, who have made much of my research possible. I am also grateful to the staffs of Manufacturing Process Lab I & III, Materials Labs, Biological & Chemical Lab, Metrology & Tribology Lab, Micromachines Lab, Thermal & Fluids Lab, Computer Aided Engineering Lab, Aerospace Structures Lab, for their kind assistance and support.
I am grateful to my fellow friends, Dr Ba Te, Ms Fang Fen, Mr Wang Dong, Dr Huang Mingxing, Mr You Siming, Dr Liu Xianbin, Dr Liu Jun and Dr Patrick Tan, for their company and extensive help.

Thanks also go to my family who have been extremely understanding and supportive of my Ph.D. study. I feel very lucky to have a family that can share my enthusiasm for higher degree pursuit.

Finally I would like to thank my wonderful wife, Lin Sanna, who has accompanied and encouraged me so much for every challenge I have taken in these years, during my M.Eng. and Ph.D. studies.
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Summary

Over the past two decades, many innovative microfluidic applications have been explored on PDMS-based devices. However, the commercialization demands have driven people to use thermoplastics as alternatives, which are more cost-efficient and amenable to high volume production process, such as micro injection molding. To address the demands of inexpensive, disposable and functional thermoplastic devices, the abilities to replicate high fidelity substrates using robust micromold at high volume, and to bond substrates with desired strength and microchannel integrity are necessary. Thus, this thesis deals with the practical fulfilment of these abilities by optimizing micro injection molding process for high fidelity and reliable replication using robust micromold, and bonding thermoplastic substrates with improved bond strength and microchannel integrity.

In this thesis, bulk metallic glass (BMG) micromold, fabricated by micro hot embossing was used in micro injection molding for high volume replication. After molding process optimization, high-fidelity microchannels can be replicated with less than 1% relative error in both depth and width. It was also found that the molding-induced residual stresses around well-formed microchannels were reprehensible on irregular microchannel deformation during the subsequent thermal bonding. Further optimization of molding process with
reduced molded-in residual stresses was conducted, which can effectively reduce the deformation irregularity from 42.7% to 8.1%. These investigations have deepened our understandings of micro injection molding parameters towards higher fidelity and more reliable replication of thermoplastic microfluidic substrates.

Thermal bonding has been initially used to seal microchannels due to its simplicity and material homogeneity; however, it was always difficult to obtain high bond strength and high microchannel integrity together. Therefore, we proposed two new approaches to address this issue. Firstly, a low temperature thermal bonding method combined with oxygen plasma treatments and low-$T_g$ polyvinyl alcohol (PVA) coating was proposed. The effects of surface modification on surface properties and bonding performance were studied. It was found that with improved surface energy and stable hydrophilicity (over one month), the coated substrates can be bonded at 30 °C lower than the glass transition temperature ($T_g$) with excellent integrity as well as sufficient bond strength for reliable micro-droplet applications. Secondly, we proposed a rapid bonding enhancement method by applying auxiliary ultrasonic actuation on intimate bonding interface. The effects of ultrasonic actuation on interfacial temperature and bonding performance were evaluated. It was found that ultrasonic energy can elevate the bonding interfacial temperature by about 10 °C and rapidly improved the bond strength by about 80% within 10 seconds, while the microchannels were free from undesired deformation due to low bulk temperature.
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<tbody>
<tr>
<td>AA</td>
<td>Acrylic acid</td>
</tr>
<tr>
<td>ANOVA</td>
<td>Analysis of variance</td>
</tr>
<tr>
<td>C₄F₈</td>
<td>Perfluorocyclobutane</td>
</tr>
<tr>
<td>CA</td>
<td>Contact angle (°)</td>
</tr>
<tr>
<td>CCD</td>
<td>Charge-coupled device</td>
</tr>
<tr>
<td>CDs</td>
<td>Compact disks</td>
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<tr>
<td>CE</td>
<td>Capillary electrophoresis</td>
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<tr>
<td>COC</td>
<td>Cyclic olefin copolymer</td>
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<td>COP</td>
<td>Cyclic olefin polymer</td>
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<td>Direct current</td>
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<td>DOE</td>
<td>Design of experiment</td>
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<tr>
<td>DOF</td>
<td>Degree of freedom</td>
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<td>DRIE</td>
<td>Deep reactive-ion etching</td>
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<td>Differential scanning calorimetry</td>
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<td>Destructive testing</td>
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<td>DUV</td>
<td>Deep ultraviolet</td>
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<td>EBL</td>
<td>Electron beam lithography</td>
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<td>EOF</td>
<td>Electroosmotic flow</td>
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<td>FTIR-ATR</td>
<td>Fourier transform infrared - attenuated total reflection</td>
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<td>HDMS</td>
<td>Hexamethyldisilazane</td>
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<td>Heat deflection temperature</td>
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<td>HEMA</td>
<td>Hydroxyethylmethacrylate</td>
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<td>Abbreviation</td>
<td>Full Form</td>
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<tr>
<td>HPLC</td>
<td>High performance liquid chromatography</td>
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<td>IBL</td>
<td>Ion beam lithography</td>
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<td>IPA</td>
<td>Isopropyl alcohol</td>
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<td>Potassium hydroxide</td>
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<td>Lab-on-a-chip</td>
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<tr>
<td>PP</td>
<td>Polypropylene</td>
</tr>
<tr>
<td>PS</td>
<td>Polystyrene</td>
</tr>
<tr>
<td>PTFE</td>
<td>Polytetrafluoroethylene</td>
</tr>
<tr>
<td>PU</td>
<td>Polyurethane</td>
</tr>
<tr>
<td>PVA</td>
<td>Polyvinyl alcohol</td>
</tr>
<tr>
<td>PVAc</td>
<td>Polyvinyl acetate</td>
</tr>
<tr>
<td>PVP</td>
<td>Polyvinyl pyrrolidone</td>
</tr>
<tr>
<td>REM</td>
<td>Replica molding</td>
</tr>
<tr>
<td>RF</td>
<td>Radio frequency</td>
</tr>
<tr>
<td>RT</td>
<td>Room temperature (~22 °C)</td>
</tr>
<tr>
<td>S/N</td>
<td>Single to noise ratio</td>
</tr>
<tr>
<td>SAM</td>
<td>Self-assembly monolayer</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>---------------------------------------------------</td>
</tr>
<tr>
<td>SAMIM</td>
<td>Solvent-assisted micromolding</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning electron microscope</td>
</tr>
<tr>
<td>SF₆</td>
<td>Sulfur hexafluoride</td>
</tr>
<tr>
<td>Tₜ₈</td>
<td>Glass transition temperature (°C)</td>
</tr>
<tr>
<td>TGA</td>
<td>Dynamic mechanical analysis</td>
</tr>
<tr>
<td>TPF</td>
<td>Thermoplastic forming</td>
</tr>
<tr>
<td>TTP</td>
<td>Time to pressure</td>
</tr>
<tr>
<td>TTT</td>
<td>Time-temperature-transition</td>
</tr>
<tr>
<td>Tₓ</td>
<td>Crystallization temperature (°C)</td>
</tr>
<tr>
<td>UV</td>
<td>Ultraviolet</td>
</tr>
<tr>
<td>VUV</td>
<td>Vacuum ultraviolet</td>
</tr>
<tr>
<td>VUV/O₃</td>
<td>Vacuum ultraviolet/ozone</td>
</tr>
<tr>
<td>Zr</td>
<td>Zirconium</td>
</tr>
<tr>
<td>δ</td>
<td>Hildebrandt parameter</td>
</tr>
<tr>
<td>μCP</td>
<td>Micro contact printing</td>
</tr>
<tr>
<td>μHE</td>
<td>Micro hot embossing</td>
</tr>
<tr>
<td>μICM</td>
<td>Micro injection compression molding</td>
</tr>
<tr>
<td>μIM</td>
<td>Micro injection molding</td>
</tr>
<tr>
<td>μPIM</td>
<td>Micro powder injection molding</td>
</tr>
<tr>
<td>μRIM</td>
<td>Micro reaction injection molding</td>
</tr>
<tr>
<td>μTAS</td>
<td>Micro total analytical system</td>
</tr>
<tr>
<td>μTF</td>
<td>Micro thermoforming</td>
</tr>
<tr>
<td>μTM</td>
<td>Micro transfer molding</td>
</tr>
</tbody>
</table>

XXII
List of Publications


- **Yu H.** and Tor S.B. A robust and rapid tooling and fabrication system for thermoplastic microfluidic devices. Singapore, 2012, *Workshop on Microfluidics for Biomedical Applications*.


Chapter 1  Introduction

1.1 Background

Microfluidics, also known as lab-on-a-chip (LOC) or micro total analytical system (μTAS) is the science and technology of system that can manipulate very small \((10^9 \text{ to } 10^{18} \text{ liters})\) amount of fluids, in closed channels with dimensions in the range of tens to hundreds of micrometers [1]. The miniaturized microfluidic devices offer the prospect of integrating multiple functions into one compact platform. In the past few years, this enabling technology has opened up a new era in the field of chemistry, cell biology, medicine and life science [2-6]. The benefits of these devices are: miniaturization, minimal analyte consumption, high resolution, fast analysis speed, high analysis throughput, low manufacturing cost and short processing time [7-11], which make microfluidics more and more attractive in both research community and industry. There have already been many professional units offering microfluidics solutions, such as Abbott Laboratories, Dolomite Microfluidics, Fluidigm, Micralyne Inc., Microfluidic ChipShop, Micronit Microfluidics and ThinXXS Microtechnology, etc.

Microfluidic devices usually embrace microstructures including microchannels, microvalves, micropumps, micropillars, microwells and reservoirs, which can be applied individually or integrated for a variety of functions, such as sample preparation, amplification, detection, capture, filtering,
mixing, pumping, etc. These microstructures can be fabricated in silicon, glass or polymer. Silicon-based devices are preferred in some circumstances because the corresponding microfabrication methods were originally derived from well-established microelectronic technologies such as lithography and etching [12]. However, silicon is relatively expensive, opaque to visible and ultraviolet light and only limited in the special clean-room level production environment. Though glass is transparent and widely used for many years [13], the high cost of producing glass-based microfluidic devices has driven people to seek other cost-efficient materials. In recent years, polymer-based microfluidic devices have become of increasing interest in biological and chemical applications due to their good biocompatibility, chemical resistance, optical properties, cost-efficiency, machinability, disposability and capability for high-volume production [14-17].

Polymers, according to their thermal properties and molding behaviours with respect to heating history, can be classified into three categories: thermosets (also known as duroplastic polymers), elastomers (also known as elastomeric polymers) and thermoplastics (also known as plastics) [14, 18]. Thermosets (i.e. photoresists) and elastomers (i.e. polydimethylsiloxane (PDMS)) are used for small volume fabrication of microfluidic devices. They are mainly adopted in laboratories for prototyping and proof-of-concept experiments. Thermoplastics are more welcome in the industry because they are less expensive and can be made in larger quantities; moreover, they can be easily produced by a variety of microfabrication technologies, such as micro hot embossing (μHE) [19, 20], micro injection molding (μIM) [21, 22] and micro thermoforming (μTF) [23, 24]. With a
pre-defined micromold (also known as tool, master or mold insert), a high volume of thermoplastic microfluidic devices can be replicated with high cost-efficiency and high reproducibility. The most typical thermoplastics used in microfluidic fabrication are polymethylmethacrylate (PMMA), polycarbonates (PC), cyclic olefin polymer (COP) and cyclic olefin copolymer (COC).

To fabricate a complete and functional thermoplastic microfluidic device, the device developer should go through three major stages: (1) design, (2) tooling and micro-replication, (3) and back-end processes [14], as shown in Figure 1-1. The back-end processes usually consist of cutting, hole drilling, metallization, bonding, surface modification, quality control and functionalization [17]. In economic terms, the back-end process could take up to 80% of the device manufacturing costs [14]. As most microfluidic devices need closed microchannels, bonding of substrates to achieve the enclosure of microchannels is a crucial step in the whole fabrication process. Several bonding methods have been proposed, including adhesive bonding, solvent bonding, thermal bonding, laser welding, ultrasonic welding and surface modifications prior to bonding [14, 25].
1.2 Motivation

The combination of thermoplastics and micro injection molding offers the bright prospect of commercializing microfluidic devices for the “killer applications”, but there are some remaining challenges associated with the tooling and micro-replication processes. Micromold, as one of the most important components in micro injection molding, should provide good robustness and reliability. Many engineering efforts have been made in the fabrication of high-resolution silicon micromolds and the machining of robust metallic micromold. However, the brittleness of silicon micromold greatly reduces its tool life and limits the replica production volume. Though micromachined steel micromold is superior in hardness, strength and wear-resistance, it is difficult and expensive to machine high-resolution microstructures for miniaturization applications. Thus, there is a need to look into other types of metallic micromolds and related tooling methods.
Furthermore, most studies of micro injection molding of thermoplastic microfluidic devices have been focused on qualitative improvement on replication fidelity, but several issues have been overlooked, such as the molding-induced polymer orientations and thermal stresses. These residual stresses are intrinsically developed during micro injection molding process, which may lead to abnormal distortion of well-formed microchannels due to stress relaxation during the subsequent bonding process. Therefore, it is imperative to study the impact of molded-in residual stresses on the microchannel dimensional integrity during thermal bonding.

Although there are a wide variety of techniques that can be used to seal microchannels, thermal bonding is of special interest because of its simplicity and the homogeneity in surface properties for all microchannel walls. However, the major issue in thermal bonding is that the high bond strength is always obtained with the big loss in microchannel integrity under high temperature over the thermoplastic glass transition temperature \( (T_g) \), or vice versa. Low bonding temperature (much lower than \( T_g \)) is ideal for microchannel integrity, but it also attributes to the low rate of bond strength development due to the intrinsically low surface energy and wettability of thermoplastics. It is also known that bond strength development is more associated with the interfacial temperature, while the microchannel deformation is more related to the bulk temperature, but it is extremely difficult to separately control the interfacial temperature and bulk temperature in pure thermal bonding process. The trade-off between bond strength and microchannel integrity should always be taken into consideration.
when thermal bonding is applied. Therefore, it is imperative to explore suitable bonding technologies to address this controversial issue, and it is highly desired to improve bond strength and microchannel integrity at the same time.

1.3 Research objectives

This thesis has the following objectives:

1. To investigate and study robust and reliable microfluidic replication process from fabrication of metallic micromold to high-fidelity replication of thermoplastic substrates via micro injection molding; to understand the key parameters needed for high-fidelity replication, and the impact of residual stresses on the microchannel dimensional integrity during molding and bonding.

2. To investigate and study applicable technologies to improve bond strength and microchannel dimensional integrity during/after thermal bonding: (1) to keep the microchannel integrity at low thermal bonding temperature, while achieving sufficient bond strength by modifying thermoplastic surface properties to facilitate bond strength development; (2) to improve the bond strength by rapidly increasing the bonding interfacial temperature, while keeping the microchannels from undesired deformation at low bulk temperature.
1.4 Thesis organization

This thesis consists of the following chapters:

Chapter 2 provides a detailed review of previous studies on microfluidic fabrication, including micromold fabrication technologies, substrate replication technologies and device bonding technologies. Characteristics of these technologies were overviewed and summarized. Chapter 3 introduces the micromold materials, device materials, and the related material characterization technologies used in this research. Chapter 4 presents the micromold fabrication processes from Si primary micromold to bulk metallic glass (BMG) micromold; the key processing parameters which affect the replication fidelity by micro injection molding were studied. Chapter 5 introduces the effects of orientational and thermal residual stresses induced by micro injection molding on the microchannel dimensional integrity during the subsequent thermal bonding process; then the micro injection molding process was optimized with reduced residual stresses. Chapter 6 presents the low-temperature thermal bonding method with surface modifications via oxygen plasma treatment and low-$T_g$ polyvinyl alcohol (PVA) coating, which can seal deformation-free and hydrophilicity-stable microchannels with acceptable bond strength for long shelf-life hydrophilic applications. The demonstration of the reliable oil-in-water droplets generation was also presented. Chapter 7 introduces the rapid bonding enhancement technique by applying auxiliary ultrasonic actuation to thermal bonding. The bond strength and microchannel integrity were analyzed and the
process mechanism was also proposed. Finally, chapter 8 summarizes the thesis with concluding remarks and recommendations for future work.
Chapter 2  Literature Reviews

2.1 Introduction

In this chapter, three major steps of fabricating polymeric microfluidic devices are reviewed. Firstly, the fabrication of micromold is introduced, including micromold materials and various micromold fabrication techniques applicable to the replication of polymeric microfluidics. Then, the replication of polymeric substrates is introduced in the second part, which covers the overview of polymeric materials followed by various replication technologies. Finally, several bonding methods to seal microchannels in thermoplastic microfluidic devices are reviewed. At each review stage, a summary of comparison and analysis is provided.

2.2 Fabrication of micromold

2.2.1 Micromold materials

Micromold for replicating polymeric microfluidic devices is a negative stamp with desired microstructures and fluidic network patterns. Three types of materials are applied to fabricate micromolds for replication of microfluidic devices: (1) silicon, (2) polymers and (3) metals.
Silicon is widely used as the micromold material in replication of microfluidic devices because there are various existing silicon microfabrication methods derived from microelectronic engineering, such as photolithography, wet etching and dry etching. Silicon can be used as a micromold in two ways. Firstly, it can be directly used as the micromold to fabricate polymeric microfluidic devices by soft lithography [26], micro hot embossing [27] or micro injection molding [28]. However, due to its brittleness, silicon micromold is mainly used in soft lithography for device rapid prototyping. In some harsh replication conditions, e.g. micro hot embossing and micro injection molding, silicon micromold usually can only last for very few replication cycles. Therefore, silicon micromold is inappropriate for high-volume replication of microfluidic devices. On the other hand, silicon can be used as the primary micromold to fabricate secondary metallic micromolds by several pattern transferring methods, such as micro powder injection molding [29] and micro hot embossing [30]. Though in these processes, the primary silicon micromold probably could be broken after only one cycle, the replicated metallic micromold is robust to produce more polymeric microfluidic substrates due to its more desirable mechanical properties.

Polymer micromolds can also be used in two ways. In the first type, the polymer is deposited on a silicon or glass wafer and patterned by various lithography techniques. This type of polymer is generally thermoset, such as photoresists, which can be patterned on wafers by photolithography to make micro- or nano- structures. In the second type of polymeric micromold, another
kind of polymer, elastomer such as PDMS, is transferred from a silicon micromold, a patterned photoresist micromold or a mechanically machined micromold. Usually, the transfer process is done through casting, and this type of elastomeric micromold is used in soft lithography process to replicate microstructures or even nano-patterns [26]. The lifetime of these polymeric micromolds is typically limited to a few tens to hundreds of replica, due to their inferior mechanical properties. Therefore, polymeric micromold is generally used in prototyping and a small volume replication of microstructure.

Metallic micromold, made with aluminum, nickel, copper, stainless steel or other alloys, can be used in various replication processes to fabricate polymeric products, such as casting, micro thermal forming, micro hot embossing and micro injection molding. Compared to silicon and polymeric micromold, the superior mechanical and thermal properties of metallic micromold ensure the long tool life replication processes. These metallic micromolds can be produced by plenty of fabrication methods. Besides several traditional but precise machining approaches, there are some advanced technologies which can be applied to produce high quality micromolds, such as micro electroforming used in LIGA (German words of Lithographie, Galvaniformung and Abformung – lithography, electroforming and molding) technology [31], and micro hot embossing of bulk metallic glass (BMG) [32].

These three classes of micromold materials are summarized and compared in Table 2-1.
Table 2-1  Overview of micromold materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>Choice of geometry</th>
<th>Lifetime</th>
<th>Material cost</th>
<th>Mold fabrication cost</th>
<th>Technology availability</th>
<th>Commercialization feasibility</th>
<th>Mold usage 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon</td>
<td>Low</td>
<td>Low - medium</td>
<td>Medium</td>
<td>Medium - high</td>
<td>High</td>
<td>High</td>
<td>Primary/Final</td>
</tr>
<tr>
<td>Polymer</td>
<td>PDMS 1</td>
<td>Medium</td>
<td>Low</td>
<td>Low - medium</td>
<td>Medium</td>
<td>Low</td>
<td>Secondary/Final</td>
</tr>
<tr>
<td></td>
<td>SU-8 1</td>
<td>Medium</td>
<td>Low</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td>Primary/Final</td>
</tr>
<tr>
<td>Metal</td>
<td>Medium - high</td>
<td>High</td>
<td>Low - medium</td>
<td>Medium - high</td>
<td>High</td>
<td>Medium - high</td>
<td>Final</td>
</tr>
</tbody>
</table>

1 PDMS and SU-8 are listed as two typical examples of polymeric micromolds.

2 Mold usage means the stage in which the micromold can be utilized in the whole fabrication process of a final micromold. (1) Primary: the micromolds can be used to make secondary or final micromolds; (2) Secondary: the micromolds can be made from primary micromolds, and can be used to make final micromolds; (3) Final: the micromolds can be obtained from primary or secondary micromolds, and can be used to replicated final parts.
2.2.2 Si microfabrication

Optical lithography, electron beam lithography (EBL), wet etching and dry etching are the most widely used microfabrication techniques to make photoresist, silicon, silicon dioxide or glass based microstructures.

In the typical process of optical lithography or electron beam lithography, a sacrificial layer of photoresist is previously deposited on a substrate wafer made from silicon or glass. After baking, this photosensitive photoresist is exposed to a dose determined irradiation (typically ultraviolet or electron beam) through a patterned mask. Chemical resistance of the photoresist changes when it is exposed to the radiation source with specific wavelength. After post-exposure baking (PEB), the exposed (or unexposed) photoresist can be dissolved by the developer for positive (or negative) photoresist, while the remaining photoresist is obtained with patterned microstructures. The typical photolithography processes of negative and positive photoresist are demonstrated in Figure 2-1.

After lithography, the pattern obtained on the substrate wafer can be transferred to the bulk of substrate wafer by dry etching or wet etching (see Figure 2-2). In wet etching, etchant is used to dissolve the substrate material by isotropic etching or anisotropic etching (orientation dependent etching), respectively for which, curved or trapezoid (or V-shaped with angle of 54.7° in etching <100> silicon) microchannel cross-sections can be obtained. In dry etching, plasma is used to remove photoresist protective layer and substrate together, while the substrate will be removed faster depending on etching selectivity. For isotropic and
anisotropic dry etching, microchannel with round or nearly vertical sidewalls can be obtained respectively. Compared to dry etching, wet etching of silicon is more favorable because the inclined sidewall and surface finish are more suitable to the demolding in replication processes. However, the isotropic etching can cause rounded microchannel cross-sections with undercuts, therefore a consistent agitation is always required.

![Schematic diagram of the typical photolithography processes with negative photoresist and positive photoresist.](image1)

**Figure 2-1** Schematic diagram of the typical photolithography processes with negative photoresist and positive photoresist.

![Schematic diagram of wet etching and dry etching.](image2)

**Figure 2-2** Schematic diagram of wet etching and dry etching.

The key drawback of silicon micromold is the limited number of replication cycles (typically less than 10), due to its brittleness and the potential
stiction problem with many polymers. Therefore, silicon micromolds are only suitable for very small volume of prototypes. However, silicon microfabrication employs various well-established techniques which make it possible to fabricate complex micro-features with high efficiency and high resolution. Therefore, silicon is the fantastic material for a primary micromold, which can be used to replicate the secondary or final micromolds.

2.2.3 Micro electroplating

The technique of micro electroplating (or electroforming) of metallic micromold is mainly used in LIGA (German words of Lithographie, Galvanoformung and Abformung) \([33, 34]\) and LIGA-like (or quasi-LIGA such as UV-LIGA \([35, 36]\) and Laser-LIGA \([37-39]\)) technologies, which have a typical fabrication process illustrated in Figure 2-3.

In a typical X-ray LIGA process, a feature design is patterned onto a layer of photoresist by an X-ray synchrotron radiation, a UV radiation or an excimer laser (step 1-2), followed by photoresist developing (step 3). Then a thin conductive layer, or namely seed layer, is deposited on the photoresist microstructure as a cathode during the electroplating process and a desired metal, usually copper or nickel is electroplated upward from the cathode layer by controlling the chemical concentration, current density and solution temperature (step 4). After photoresist removal and polishing (step 5), the electroplated block can be used as a micromold to replicate microstructures onto polymeric
substrates through several replication techniques (step 6), such as micro injection molding and micro hot embossing.

![Figure 2-3 Schematic diagram of a typical LIGA process to fabricate electroplated (or electroformed) metallic micromold for replication of polymeric part (e.g. stamp for hot embossing) (Courtesy of Singapore Synchrotron Light Source).]

LIGA process can produce the metallic micromold with high resolution and high aspect ratio microstructures [14]. However, LIGA technology using synchrotron radiation X-ray source is extremely expensive, which make it unrealistic to be widely afforded in academia or be adopted in industry to produce metallic micromold in a large batch. To avoid the expensive source of X-ray LIGA, UV-LIGA and Laser-LIGA techniques are more preferable due to their cost-efficiency. But compared to X-ray LIGA technology, LIGA-like technologies are proposed and employed at the cost of critical dimensional resolution and microstructure aspect ratio. Moreover, the electroplating process employed in all types of LIGA technologies is quite time-consuming from a few hours up to weeks, and the electroplating rate is sensitive to the distribution of
microstructures which make it necessary to grind and polish the uneven surface after electroplating.

### 2.2.4 Precision micromachining

Several precision micromachining technologies have been applied to fabricate metallic micromolds, such as high-precision micromilling, laser micro-machining, and micro electrical discharge machining, etc.

Mechanical micromilling uses ultra-small tools to machine miniaturized components with high precision [40-43]. High-precision micromilling offers some distinct advantages over other commonly used techniques for micromold fabrication. For example, its process is very straightforward, compatible to a wide selection of materials and capable of machining non-standard or three-dimensional (3D) structures. In contrast, silicon microfabrication and micro electroplating techniques are suitable to very few limited materials. Though the resolution of micromilled microstructures is inferior to those fabricated by silicon related technologies, micromilling is capable to easily, rapidly and economically fabricate microscale features in the order of 50 to 100 μm [44], which are well suitable for many microfluidic applications [43]. However, a few drawbacks of micromilling should be noted, including relatively large wall roughness, machining marks, tool diameter limitation, and unavoidable large machined rounded corners.

Laser micromachining, also known as laser ablation, is a process that removes material line by line and layer by layer. During this process, the
vaporization of material occurs as a result of interaction between the laser beam and the material being machined. Laser micromachining provides the convenience to machine microstructures in materials directly from CAD designs [45, 46]. This technique is capable of machining metallic materials [47, 48] and polymeric materials [49], both of which can be used to make the micromolds for replication. Laser micromachining has already proved its potential to make rapid and cost-efficient toolings for the replication of microfluidics [50, 51]. However, there are several drawbacks in laser micromachining of microchannels. Poor surface roughness is one of the limitations, resulting from the debris and melt generated during laser ablation. The Gaussian shape of microchannel is another engineering issue, which is mainly attributed to the uneven intensity of the laser beam as well as the variant reduced laser absorption at sloped contours [49].

Micro electrical discharge machining (μEDM) comes from conventional electrical discharge machining (EDM), which is an enabling technique for processing conductive hard and brittle material [52, 53], including hardened steels and tool steels. The material removal mechanism if based on spark-erosion effect, which is created by separating positive and negative electrodes with a small gap and applying high voltage. The high temperature caused by electrical discharging can facilitate the removal of targeted material through melting and sublimation. There are several variations of μEDM: micro die-sinking EDM, micro-wire EDM (μWEDM), micro-EDM drilling, micro-EDM milling and micro-EDM grinding [54, 55]. Micro electrical discharge machining shows several advantages such as high geometry freedom and high aspect ratio; therefore it has
been used as a structuring technology to fabricate micro-toolings for microstructure replication such as microchannels [55, 56]. However, there are some intrinsic engineering issues associated with this method. For example the prerequisite mold electrode should be pre-defined before the implementation of micro die-sinking EDM and the wear of mold electrode should be well evaluated and estimated. As to micro-wire EDM, several issues should be noted, such as handling of micro wire (down to 0.02 mm [55]), accuracy loss and surface quality due to wire vibration.

2.2.5 Micro powder injection molding

Micro powder injection molding (μPIM) combines the technologies of plastic injection molding and powder metallurgy to produce net-shape metal, ceramic or hard materials [57-59]. The four major processing steps in micro powder injection molding are illustrated in Figure 2-4, including (1) mixing of powder and binder to prepare feedstock, (2) micro injection molding to replicate microstructure from the micromold, (3) debinding to remove the binder constituents, and (4) sintering to improve mechanical properties.

Micro powder injection molding has a number of advantages, including high shape complexity, high replication accuracy, net-shape or near net-shape formability, wide materials availability and cost-efficiency [58]. On the other hand, there are also some limitations to be addressed. For example, the commercial feedstock is limited in powders with fine size distribution; the minimum feature size and surface roughness are limited due to powder grain
size; the porosity and shape distortion due to the shrinkage during debinding and sintering are inevitable; and the cycle duration is quite long because of the time-consuming debinding and sintering processes.

![Diagram of micro powder injection molding process](image)

*Figure 2-4* Schematic diagram of a typical micro powder injection molding process including feedstock preparation, micro injection molding, debinding and sintering [58].

### 2.2.6 Thermoplastic forming of BMG

In both precision micromachining and micro electroplating technologies, the crystalline structures of conventional metals can result in nonuniform properties at the length scale of their structure [60], which is a significant limitation in micro- and nano-scale applications. In contrast, bulk metallic glasses (BMGs), a class of amorphous metallic alloys, are microscopically homogeneous and isotropic [60]. In addition, BMGs are strong, highly elastic, corrosion resistant,
wear resistant and plastic at small scales [61, 62]. Furthermore, they can be formed at low temperature by direct die-casting and thermoplastic forming (TPF) [63, 64], to create precise geometries with length scales ranging from tens of nanometers to several centimeters [63, 65, 66].

Thermoplastic forming has proven to be a promising method of processing BMGs (e.g. micro hot embossing), which is inexpensive, reproducible and predictable [30, 32, 67-73]. In a typical TPF process (see Figure 2-5(a-c)), a BMG plate and a primary micromold (e.g. a predefined silicon micromold) are heated into the supercooled liquid region above the glass transition temperature ($T_g$) of BMG, after which, the viscous BMG is compressed onto the mold to replicate microstructures. Then the BMG is separated from the primary micromold to get either surface-patterned BMG or 3D patterned BMG.

![Figure 2-5](image.png)  
**Figure 2-5**  Schematic diagrams of (a-c) thermoplastic forming process to fabricate BMG molds (with surface and free-standing 3D components), and (d) time-temperature transformation [60].
The key challenge in BMG processing methods is to avoid crystallization. Figure 2-5(b) shows a typical schematic time-temperature-transformation (TTT) diagram of BMG. Path 1 demonstrates the process of direct die-casting through rapid cooling to bypass the crystallization region; however it is not a suitable process for microstructure fabrication due to the limited processing time. Path 2 demonstrates the process of thermoplastic forming. The BMG is reheated to the supercooled state above its glass transition temperature, which is stable over a wide time-temperature window. Therefore, it is more controllable to process BMGs with thermoplastic forming techniques. Moreover, thermal embrittlement is another widely observed phenomenon [74-77]. Embrittlement correlates with the structure relaxation when the annealing temperature is below $T_g$, while crystallization dominates this phenomenon when the temperature is elevated to above $T_g$. However, thermoplastic forming above $T_g$ does not cause embrittlement.

Thermoplastic forming of BMGs offers an excellent opportunity to fabricate complex and precise BMG microstructures for miniaturization applications. Recently, many experiments [32, 70, 72, 78, 79] and numerical simulations [68, 72, 80, 81] have been conducted to fabricate microstructures and nanostructures on BMGs by thermoplastic forming, but there is still little practice on the replication of thermoplastic microfluidic devices with BMG micromold [32, 82].
2.2.7 Summary

To select an appropriate micromold fabrication method, several criteria should be taken into consideration, such as feature geometry and size, micromold material, cost-efficiency, material manufacturability, fabrication precision, micromold surface finish and micromold lifetime. A summary of above described fabrication methods of micromold is listed in Table 2-2. Based on the review analysis of micromold fabrication methods, it is suggested that a more robust and reliable micromold fabricated in BMG by a straightforward thermoplastic-based micro hot embossing process is highly desirable for fabrication of polymeric microfluidic devices in a high volume.
Table 2-2  Overview of micromold fabrication methods for microfluidic devices.

<table>
<thead>
<tr>
<th>Process</th>
<th>Geometry choice</th>
<th>Typical materials</th>
<th>Material cost</th>
<th>Process cost</th>
<th>Micromold lifetime</th>
<th>Surface finish</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon microfabrication</td>
<td>Low - medium</td>
<td>Si, Glass</td>
<td>Low - medium</td>
<td>Medium - high</td>
<td>Low</td>
<td>Fair</td>
</tr>
<tr>
<td>Micro electroplating</td>
<td>Medium - high</td>
<td>Nickel</td>
<td>Low - medium</td>
<td>Low</td>
<td>Long</td>
<td>Fair</td>
</tr>
<tr>
<td>Precision micromachining</td>
<td>Low - medium</td>
<td>Stainless steel,</td>
<td>Low</td>
<td>Medium - high</td>
<td>Medium - long</td>
<td>Fair - good</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Brass, Aluminium</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Micro powder injection molding</td>
<td>Medium - high</td>
<td>Stainless steel</td>
<td>Medium</td>
<td>Medium - high</td>
<td>Medium - long</td>
<td>Poor</td>
</tr>
<tr>
<td>Thermoplastic forming of BMG</td>
<td>Medium - high</td>
<td>Amorphous metals</td>
<td>Medium - high</td>
<td>Low</td>
<td>Long</td>
<td>Good</td>
</tr>
</tbody>
</table>

1 Only silicon- and metal- based materials are considered here.

2 Only micro electroplating process is considered here, instead of the whole process of LIGA or LIGA-like technology.
2.3 Replication of polymeric substrates

2.3.1 Polymeric substrate materials

There is an increasing interest in disposable microfluidic devices which are very important in biological and medical application [83]. Polymers are suitable for high volume fabrication of microfluidic devices mainly for two reasons. Firstly, a distinct merit is that polymeric materials with specific physical and chemical properties can be easily accessed, such as machinability, stiffness, molecular adsorption, electroosmotic flow (EOF) mobility, optical properties, chemical resistance, surface tension, etc [7, 83]. Secondly, in industrial manufacturing, there are various commercially available fabrication technologies. Different fabrication methods may require different and specific properties of polymeric materials [7]. For example, in micro hot embossing, the glass transition temperature is the most crucial parameter. According to physical classification with respect to shape transformation upon exposure to heat [83], polymers can be subdivided into three categories: thermosets, elastomers and thermoplastics. The summary of several substrate materials: silicon, glass and polymers, is listed in Table 2-3.
### Table 2-3: Overview of materials for microfluidic device fabrication [14].

<table>
<thead>
<tr>
<th></th>
<th>Silicon</th>
<th>Glass</th>
<th>Thermosets</th>
<th>Elastomers</th>
<th>Thermoplastics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microfabrication feasibility</td>
<td>Easy – medium</td>
<td>Easy – medium</td>
<td>Medium</td>
<td>Easy</td>
<td>Easy</td>
</tr>
<tr>
<td>Microfabrication process</td>
<td>Wet and dry etching</td>
<td>Wet-etching, photostructuring</td>
<td>Lithography, etching, casting</td>
<td>Casting</td>
<td>Injection molding, hot embossing, thermoforming, laser ablation</td>
</tr>
<tr>
<td>Possible geometries</td>
<td>Limited, 2D</td>
<td>Limited, 2D</td>
<td>Mostly 2D, 3D possible</td>
<td>Mostly 2D, 3D possible</td>
<td>Many, 2D, 3D</td>
</tr>
<tr>
<td>Assembly feasibility</td>
<td>Easy</td>
<td>Medium</td>
<td>Medium</td>
<td>Easy</td>
<td>Easy</td>
</tr>
<tr>
<td>Interconnections</td>
<td>Difficult</td>
<td>Difficult</td>
<td>Easy</td>
<td>Easy –medium</td>
<td>Easy</td>
</tr>
<tr>
<td>Temperature stability</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>Very low</td>
<td>Low –medium</td>
</tr>
<tr>
<td>Acid stability</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>Mostly high</td>
</tr>
<tr>
<td>Alkaline stability</td>
<td>Limited</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>Mostly high</td>
</tr>
<tr>
<td>Organic solvent stability</td>
<td>High</td>
<td>Medium –high</td>
<td>Medium –high</td>
<td>Low</td>
<td>Low –medium</td>
</tr>
<tr>
<td>Optical transparency</td>
<td>No</td>
<td>High</td>
<td>Partly</td>
<td>High</td>
<td>Mostly high</td>
</tr>
<tr>
<td>Material price</td>
<td>Medium</td>
<td>Medium –high</td>
<td>Medium</td>
<td>Low</td>
<td>Low –medium</td>
</tr>
</tbody>
</table>

26
Thermosets can be cured (crosslink) upon heating or exposure to radiation, and the generated molecular network is rather strong which cannot be easily broken by re-heating or re-exposure. Therefore, once cured, thermosets are usually temperature stable. Its glass transition temperature normally is quite high and close to the decomposition temperature, which means upon heating, it will eventually decompose and burn instead of melting. Typically thermosets in microfabrication are commonly used photoresists, such as positive photoresist AZ series and negative photoresist SU-8 series. The fabrication of above mentioned thermosets are related to microelectronic techniques, especially photolithography, but they are limited to special fabrication environment and equipment.

Elastomers usually have low glass transition temperature well below operating temperature. Elastomers have longer molecular chains than the other two types of polymers which are mainly physically entangled. The long polymer chains can also crosslink during curing process. With external but not extensive force, cured elastomer can stretch elastically and recover to the original state when the external force is released. The elastic property makes elastomers ideal materials for movable components such as micropumps. PDMS, as the most widely used elastomer, has become a primary option for rapid prototyping of microfluidic devices in laboratories due to several merits:

(1) Inexpensive raw material;
(2) Transparent at optical frequencies (240 nm – 1100 nm);
(3) Elastic to undergo distortions for application of active elements like valves and pumps;

(4) Low auto-fluorescence and biocompatible which is applicable to some bioengineering applications;

(5) Permeable to gas which can allow O₂ supplying in cell culture devices;

(6) Straightforward, flexible, reproducible, and high resolution (down to a few nanometers) rapid prototyping method: replica molding;

(7) Reliable and robust bonding to PDMS or glass via plasma treatment, which allows the production of multilayer microfluidic devices and the deposition of thin layer metal or dielectrics;

On the other hands, PDMS still has some shortages which limit its application for higher volume fabrication, including:

(1) Poor mechanical strength;

(2) Low elastic modulus which bounds the working pressure below 1 bar;

(3) Swelling upon most organic solvents which limits its use to aqueous solutions;

(4) Permeability to water vapor which can lead to device drying or changes in medium osmolarity;

(5) Absorption of small hydrophobic molecules onto its surface like proteins and drugs;

(6) Unstable wettability after surface modification due to hydrophobic recovery.
Besides PDMS, fluorinated elastomers [84, 85] also have gained increasing interest. They exhibit a number of good properties such as low surface tensions, good biocompatibility and high chemical resistance. However, compared to PDMS, fluorinated elastomer precursors are relatively expensive and are difficult to be obtained commercially.

Thermoplastics are the most widely used materials in high volume production of polymer products. For thermoplastics, no crosslinking or curing occurs at a reasonably elevated temperature; therefore thermoplastics can be re-shaped many times by reheating. Glass transition temperature is the characteristic thermal property associated with processing, above which, thermoplastics start to soften and can be formed around this temperature. Usually, there is a large temperature difference between glass transition and decomposition, which results in a wide processing window. Another appealing merit of thermoplastics based microfluidic devices is that there are a lot of replication methods commercially available. Both in academia and industry, many classical thermoplastic polymers have been proposed to fabricate microfluidic devices, such as Polymethyl methacrylate (PMMA), Polycarbonates (PC), Polypropylene (PP), Polystyrene (PS), Polyethylene (PE), Cyclic olefin copolymer (COC), Cyclic olefin polymer (COP), Polyether ether ketone (PEEK), etc.
2.3.2 Soft lithography

As its term defined, soft lithography uses soft elastomeric polymer as the stamp, mold or mask to generate micro-patterns or microstructures [26]. In the earliest experimental method, an elastomeric stamp was used with a layer of chemical ink to form self-assembly monolayer (SAM) on a substrate [86]. Then its ability has been developed and several variants have been proposed (see Figure 2-6), including micro contact printing (μCP), replica molding (REM), micro transfer molding (μTM), micro molding in capillaries (MIMIC), solvent-assisted micromolding (SAMIM) etc [26].

Typically, soft lithography process can be separated into two parts: preparation of elastomeric substrate/micromold and generation of structures defined by the elastomeric micromold. These two steps are totally different, but either of them can be used to fabricate microstructures. In the first step, PDMS is commonly prepared as elastomeric substrate or micromold which can be used to transfer microstructures by replica molding [87]. The preparation process is composed of three steps: casting, curing and releasing. Firstly, mixture of silicone elastomer and curing agent is poured over the primary micromold in a Petri dish; then it is cured at an elevated temperature; finally it is peeled off and cut to proper size. This process has been widely utilized for rapid prototyping of microfluidic devices.

In the second step of soft lithography, the obtained elastomeric micromold can be used either as stamps for printing (such as micro contact printing), or as
soft micromold for imprinting (such as solvent-assisted micromolding). With a number of applications, soft lithography has proved to be capable of patterning not only self-assembly monolayer (SAM), but also proteins, cells and DNA. However, there are some technical issues associated with soft lithography: for example, shrinking during curing, collapse and buckling of PDMS structures in printing, substrate contamination by uncured PDMS fragments or impure SAM, swelling of PDMS stamp induced by most organic solvents, etc.

Figure 2-6  Schematic diagram of several soft lithography variants: (A) micro contact printing ($\mu$CP), (B) replica molding (REM), (C) micro transfer molding ($\mu$TM), (D) micro molding in capillaries (MIMIC), (E) solvent-assisted micromolding (SAMIM) [26].
2.3.3 Micro hot embossing

It has been reviewed in the previous section that micro hot embossing can be used to fabricate BMG micromold. However, this technology is better known for polymer replication. Micro hot embossing offers great potential to polymeric structures in the scale of several micrometers [19, 27] or even sub-100 nanometers [88-90], for the latter, which is also known as nanoimprint lithography (NIL). The typical process of micro hot embossing is illustrated in Figure 2-7. Firstly, polymeric substrate (sheet or film) is clamped by two platens. Micromold is mounted on the mold. The platens and substrate are heated just above the \( T_g \) of polymer in a vacuum environment. Evacuation tools are used to generate vacuum in a chamber for better filling of polymer into microcavities. Then, compression force is applied onto the platens for certain duration, resulting in the softened polymer filling in the microcavities on the micromold. Finally, the platens and substrate are cooled down to a temperature much lower than the \( T_g \) of polymer, and the substrate is released from the micromold by demolding.

![Figure 2-7 Schematic diagram of micro hot embossing process](image-url)

Figure 2-7 Schematic diagram of micro hot embossing process [22]
Micro hot embossing is an advantageous replication method for many reasons: the cost of thermoplastic polymer is low, the material selection is flexible, the system setup is fast, the temperature cycle between embossing temperature and demolding temperature is short, and the residual stress generated in polymeric parts is reasonably moderate due to short flow path of polymer.

On the other hand, the major issue of micro hot embossing is long cycle time, sometimes up to 30 minutes, which dramatically decreases the throughput compared with micro injection molding. Variotherm process is the major reason for long cycle time, which involves both heating and cooling steps in one embossing cycle. There are several potential solutions, for example, the temperature cycle can be further shortened, fast heating and cooling tools can be employed and automation can be designed to continuously feed polymer substrates. However, more residual stress will be caused by extreme fast cooling.

Lately, some new types of micro hot embossing technique have been proposed, such as roll-to-roll hot embossing [91-97] and ultrasonic hot embossing [98-106]. Roll-to-roll hot embossing supplies an alternative method for large scale hot embossing, which shows a great potential for high volume production. Both simple microstructures [91-97] and continuous microfluidic patterns [91, 93, 95, 96] can be embossed on film substrates. Ultrasonic hot embossing is proposed to get a better filling by ultrasound induced localized heating and to shorten cycle time with the assistance of ultrasonic vibration.
2.3.4 Micro thermoforming

Thermoforming is a well-established fabrication process for food packaging, plastic cups and car bumpers replication. It also shows high probability for microfabrication of 3D products with thin sidewalls in microscale [107]. Lately, micro thermoforming has become a new class of polymer micromolding process for fabrication of microfluidic chips [23, 24, 108, 109]. There are two basic types of thermoforming processes, positive forming and negative forming, in which positive micromold with protrusions and negative micromold with cavities is used, respectively. Different variants of micro thermoforming have been developed, including micro matched-die molding (forming with a matching counter mold), rubber-assisted hot embossing (forming with an elastomeric counter mold), micro back molding (forming with a softened second polymer), and micro pressure forming (forming with compressed gas) [107].

In a typical micro thermoforming process (usually micro pressure forming) as shown in Figure 2-8, a semi-finished film of thermoplastic polymer is placed between platens. These platens contain a micromold with microstructures and through holes for evacuation and gas pressurization. After evacuation, the platens together with the film are heated up just above $T_g$ of the polymer, then a compressed gas is supplied to form the film onto micromold. Then the molds are cooled down, the gas pressure is decreased, and the thermoformed film is demolded from the micromold. Micro thermoforming shows great potential of replicating 3D dimensional structures. Nevertheless, there are still some problems that need to be overcome. According to its principle, thermoformed
film has discrepant sidewall thickness. For high aspect ratio microstructure, the film may be overstretched and broken. Moreover, it is very difficult to thermoform structures with sharp corners and sharp edges. Micro thermoforming is still in its early developing stage, and to our best knowledge, there is still a lack of commercially available micro thermoforming system for microstructure fabrication.

![Diagram of micro thermoforming process](image)

Figure 2-8 Schematic diagram of a typical micro thermoforming process: (a) evacuation and heating up of the tools, (b) forming of the plastic film by compressed gas and cooling down the tools, and (c) demolding the thermoplastic film from micromold. (1) Platen with micromold, (2) vacuum, (3) thermoplastic film, (4) seal, (5) counter plate, (6) compressed nitrogen, (7) thermoformed film microstructure [24].

### 2.3.5 Micro injection molding

Thermoplastic micro injection molding is a process of molding a thermoplastic polymer from the molten state in heated barrel to the re-solidified state in microcavities as shown in Figure 2-9. Solid polymer pellets are heated up to their melting temperature and the molten polymer is injected into microcavities by
high molding pressure. By holding the pressure for a specific duration, the molten polymer is allowed to re-solidify because the mold temperature is lower than its $T_g$. Then the molds are opened and the molded polymeric part is ejected. A typical cycle lasts between a few seconds and one minute [28].

Micro injection molding is the most preferred high volume manufacturing technique to replicate polymeric products because of several advantages, including wide polymer selection, mass manufacturability, cost-efficiency, short cycle time, potential of full-automation and available simulation tool (e.g. Simulation Moldflow of Autodesk). There are several commercially available injection molding systems supplied by Battenfeld, Mitsubishi, Nissei and Arburg, etc.
There are some other types of micro injection molding that have been proposed, such as micro reaction injection molding (μRIM) and micro injection compression molding (μICM). Micro reaction injection molding includes mixing and injection of two or more liquid polymers (monomer and initiator). Micro injection compression molding is a well-known process for producing compact disks (CDs). It integrates a compression step with polymer injection, which can reduce the negative effects resulted from long flow path in conventional micro injection molding. Thus it is potential of producing large scale CD-like centrifugal microfluidic platforms [110, 111].

Despite of the well-establishment and availability of large amount of know-how in micro injection molding, there are still some challenges for replication of microfluidic devices. It has been reported that microstructure with higher aspect ratio is difficult to be molded because of the hesitation effect phenomenon [112, 113] and the concept of time to pressure (TTP) [114]. The former concept means that the molten polymer is apt to flow into cavities with larger cross section area and lower resistance. The latter term explains the fact that the degree of filling depends on the distance from the injection gate. Variotherm mold can be used to get higher aspect ratio yet at the cost of increasing cycle time [115].

Moreover, due to long flow path and non-isothermal condition, high residual stresses can be induced in molded polymers, which is the intrinsic characteristic to all injection molding techniques [116]. These residual stresses can cause instability of microchannel dimension [117], viscoelastic deformation [118], cracking [119] and sensitivity to chemical diffusion [120]. In literatures, there are
many efforts made on improvement of microfluidics replication fidelity by micro
injection molding [121-124]. However, the residual stresses molded in
thermoplastic microfluidic substrates have been overlooked for many reasons.
Several conventional destructive testing (DT) techniques, such as layer removal
and hole drilling, can be used to determine the stresses in molded macro-parts.
However, they are inapplicable to evaluate the stresses in molded products with
microstructures. Currently, there is still a research gap to be filled in order to
qualitatively and quantitatively evaluate the effects of molded-in residual stress
on back-end process and application of thermoplastic microfluidic devices.

2.3.6 Summary

Table 2-4 provides an overview of several characteristics of above described
replication methods. To replicate microfluidic devices, it is suggested that the
following criteria should be taken into consideration.

(1) The pattern design need to be determined, including the type of micro-
structures (e.g. channels, pillars, wells, reservoirs) and the microstructures
aspect ratio;

(2) The device materials should be determined, thermosets, elastomers or
thermoplastics;

(3) The batch size of replication should be predefined, which closely
corresponds to the cost-efficiency of production;
Once the above aspects have been determined, the replication process should be properly selected and certain fabrication issues should be addressed according to the characteristics of the selected process.
Table 2-4  Overview of replication methods for polymeric microfluidic device [14, 18, 125]

<table>
<thead>
<tr>
<th></th>
<th>Soft lithography (casting)</th>
<th>Micro hot embossing</th>
<th>Micro thermoforming</th>
<th>Micro injection molding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymer type ¹</td>
<td>Elastomers</td>
<td>Thermoplastics</td>
<td>Thermoplastics</td>
<td>Thermoplastics</td>
</tr>
<tr>
<td>Raw material</td>
<td>Liquid prepolymer and</td>
<td>Sheet or film</td>
<td>Film</td>
<td>Pellets</td>
</tr>
<tr>
<td></td>
<td>curing agent</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Processing window ²</td>
<td>Ambient to curing</td>
<td>Glass transition</td>
<td>Glass transition</td>
<td>Glass transition range</td>
</tr>
<tr>
<td></td>
<td>temperature</td>
<td>range</td>
<td>range</td>
<td>range to melting</td>
</tr>
<tr>
<td>Typical cycle time</td>
<td>Long,</td>
<td>Medium –long,</td>
<td>Medium,</td>
<td>Short - medium,</td>
</tr>
<tr>
<td></td>
<td>Less than 1 hour</td>
<td>5-10 minutes</td>
<td>20 minutes (laboratory)</td>
<td>Few seconds to few minutes (variotherm)</td>
</tr>
<tr>
<td>Tool cost</td>
<td>Low</td>
<td>Low - medium</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Set-up time</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Flexibility</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>Volume production</td>
<td>Low</td>
<td>Low - medium</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Automation</td>
<td>Laboratory</td>
<td>Laboratory and</td>
<td>Laboratory</td>
<td>Highly automated</td>
</tr>
<tr>
<td></td>
<td></td>
<td>automated</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

¹ Only polymeric materials are taken into account here.
² Only temperature is considered here for comparison.
2.4 Bonding of devices

2.4.1 Adhesive bonding

Adhesive bonding is widely used for joining various products due to its simplicity. For miniaturised applications, adhesive bonding has also been discussed as a feasible method to bond polymeric microfluidic devices [14, 25, 126]. In a typical adhesive process, a thin layer of liquid adhesive or adhesive film is cured by UV irradiation (UV-curable adhesive), by heat (heat sensitive adhesive) or by pressure (pressure sensitive adhesive). PDMS has also been used to join PMMA substrates [127]. There are several variants of adhesive bonding method, for instance, adhesive interstitial bonding [128], adhesive contact printing bonding [129] and lamination film bonding [130] as shown in Figure 2-10.

![Diagram of adhesive bonding processes]

Figure 2-10  Schematic diagram of several adhesive bonding processes: (a) adhesive interstitial printing bonding [128], (b) adhesive contact printing bonding [129] and (c) lamination film bonding [130].

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Adhesive bonding shows a lot of advantages, including simplicity, variety of available adhesive liquids or lamination films and high bond strength. Lamination film bonding is high throughput and scalable, which makes it well feasible for mass production of thermoplastic microfluidics [25]. However, the viscosity of all the employed adhesives should be high enough to avoid the clogging of microchannels, which is the key challenge of adhesive bonding. Moreover, the introduction of foreign material into microfluidic devices may contaminate microchannels and result in inhomogeneity properties, which probably could affect the consistency during application.

2.4.2 Solvent bonding

Solvent bonding is a process in which the surfaces of polymeric parts to be bonded are treated with a solvent, brought into contact and clamped together under a given pressure. Despite of many similarities, there is an evident difference between solvent bonding and adhesive bonding. Solvent bonding of polymers takes advantage of polymer solubility in certain solvents to achieve entanglement of polymer chains across the bonding interface [25] instead of adhesion by adhesives. The solubility between organic solvents and polymers is described by Hildebrandt parameter (δ), also named solubility parameter, which is defined as the square root of the cohesive energy density. Materials with similar solubility parameters can interact with each other and miscibility or dissolution of the solute can occur. For commonly used amorphous non-polar
polymers, similar solubility parameters of between polymer and solvent will result in good solvation and strong bonding. Therefore, solvent bonding can produce relatively higher bond strength compared to other bonding methods.

In a typical solvent bonding process, solvent can be applied to the bonding surfaces either in liquid or in vapour phase. PMMA devices can be sealed by variety of liquid solvent such as acetone, ethanol, methanol, isopropanol, acetonitrile and some mixed solvent system [131-138]. COC devices, which have gained much attention in high performance liquid chromatography (HPLC) application, have to provide high bond strength on the order of 10-40 MPa [139]. Several solvent bonding processes of COC chips have been reported, for example, the use of mixture of ethanol and decalin [140] and the use of cyclohexane vapour followed by deep UV (DUV) irradiation [141].

The major advantages of solvent bonding are: simplicity, cost-efficiency, higher bond strength superior to other bonding methods and scalability from prototyping to mass production. But there are still some distinct limitations, including inhomogeneity of microchannel surface properties due to the use of chemicals, solvent retention due to irreversible physical absorption of the low molecular solvent in the polymer bulk, and microstructure deformation due to excessive solvation. It was reported that acetone could dissolve PMMA and cause microchannel deformation when the solvent exposure time was longer than 2-3 seconds [134]. To avoid microchannel deformation, sacrificial phase-change materials have been studied as a reliable solution, such as wax [132] (see Figure 2-11) and water [142].
Figure 2-11  Schematic diagram of solvent bonding process using wax as sacrificial filling material: (a) enclosing microchannel with temporary PDMS cover, (b) filling liquid paraffin wax at raised temperature, (c) cooling to solidify the wax, moving PDMS cover to the opposite side as exterior protector and coating acetonitrile, (d) bonding to a second blank PMMA piece with PDMS exterior protector, and (e) heating to melt the wax with assistance of vacuum and dissolution of cyclohexane [132].

2.4.3 Thermal bonding

Thermal bonding (also as known as thermal compression bonding, thermal fusion bonding and thermal diffusion bonding) is one of the simplest bonding techniques, in which, clean and flat polymer substrates are clamped and heated to a temperature near the \( T_g \) of polymer under a given compression pressure for a period of time (see Figure 2-12). With the applied heat and pressure, polymer chains diffuse across the bonding interface resulting in strong bond between two surfaces. The rate of diffusion not only depends on the bonding parameters but also depends on the polymer molecular weight [143, 144]. Surface wetting is another process that contributes to the development of interfacial bond at polymer interface [145]. It is attributed to van der Waals forces at the interface between two contacting surfaces.
Thermal bonding is versatile for various polymers and capable of bonding dissimilar polymers. When identical polymers are bonded, the homogeneous microchannels with uniform surface properties can be obtained after bonding, which is one of the most important advantages of thermal bonding for microfluidics fabrication. However, the major challenge in thermal bonding is microchannel deformation caused by high bonding temperature and pressure, resulting in big loss in microchannel integrity. On the other hand, when low temperature and pressure are applied, the resulting bond strength is often lower than the desired value, causing some limitations in applications, such as liquid chromatography where high internal fluid pressure is required [139]. Moreover, long cycle time of thermal bonding is another processing issue for high throughput bonding.

Due to its simplicity and material homogeneity, thermal bonding is widely used as a direct bonding method for microfluidic device fabrications [51, 144, 146-158]. In order to achieve acceptable bond strength while keeping microchannel out of deformation, many efforts have been done to optimize the bonding process, such as same base polymers with different molecular weights.
same base polymers with different grades of glass transition temperatures [144], high temperature with low pressure [51], high pressure with low temperature [151]. To improve bonding performance, other techniques should be used as an assistant condition, for example, surface modification or ultrasonic bonding, which will be reviewed in the following sections.

2.4.4 Ultrasonic welding/bonding

Ultrasonic welding is a well-established process to join polymer parts made from any thermoplastic [159]. In a typical ultrasonic welding method, as shown in Figure 2-13, the polymer parts to be bonded are fixed on an anvil, and an ultrasonic horn (sonotrode) is pressed onto the parts with oscillating compression in high frequency (over 20 kHz). Ultrasonic energy transmits through booster and horn to the polymer parts, which then induce localized heating, softening and melting of auxiliary structures, namely energy directors, to join the polymer parts. The generated heat is the result of intermolecular and interfacial friction [160]. The whole ultrasonic welding process typically can be finished within only a few second, which shows great potential for rapid and high volume production. Recently, this method has been introduced to weld microparts for microfluidic applications [159, 161-165]. These microparts were joined together by the molten micro energy directors, which could localize ultrasonic energy and weld the bonding surfaces. However, this method has not been widely adopted for microfluidic fabrication because of an intrinsic disadvantage that it needs special design and fabrication of energy directors in the microscale to effectively focus
ultrasonic energy. The fabrication cost, therefore, is highly increased especially when the energy directors are formed on the same substrate with microchannels as shown in Figure 2-14(a-b). Even if the energy directors can be located on the counter part, as shown in Figure 2-14(c), precise alignment becomes another issue. Furthermore, the control of molten energy directors in the microscale is another big challenge, which may lead to bonding failures, such as gap and microchannel clogging, as shown in Figure 2-15. Till now, there is still a big know-how vacancy on design protocol of and precise melting control of micro energy director for micropart welding.

![Figure 2-13 Schematic diagram of ultrasonic welding process [159].](image)
Figure 2-14  (a) SEM micrographs of injection-molded COC Y-junction microchannel and detection chamber with surrounding micro energy directors [164], (b) schematic diagram of COC PCR reaction chamber with surrounding micro energy directods [165], and (c) micrograph of 500 μm wide and deep microchannel sealed by ultrasonic welding [161].

Figure 2-15  Micrographs of microchannel (a) with energy directors before ultrasonic welding and (b-c) undesirable welding results after ultrasonic bonding: (b) gap around the channel after bonding and (c) clogging of microchannel [166].
In the past four years, Zhang and Luo have published a series of work on a promising ultrasonic bonding process for microfluidics fabrication [166-170]. In this method, ultrasonic energy has been introduced in a rapid bonding process of flat thermoplastic microfluidic substrates without micro energy director, as shown in Figure 2-16(a) [167]. In contrary to ultrasonic welding, there is no polymer melting involved in this new bonding method. The use of ultrasonic energy can be integrated into other well-known bonding methods, such as solvent bonding [166] and thermal bonding [168-170]. In the hybrid solvent-ultrasonic bonding method, the applied ultrasonic vibration can elevate the interfacial temperature and increase the solubility of PMMA in IPA. The proposed bonding principle in the hybrid thermal-ultrasonic bonding is that the diffusion of polymer molecules on the bonding interface can be improved due to elevated interfacial temperature and oscillating compression force. It was reported that the proposed thermal-ultrasonic bonding method could bond PMMA substrates at temperature 20–30 °C lower than its T_g in tens of seconds with good bond strength and minor microchannel deformation [170]. Moreover, it was applicable to bond multilayer (up to 12 layers) PMMA microfluidic, as shown in Figure 2-16(b) [169] and planar nanofluidic devices [168]. However, there are very limited research articles reported on the application of ultrasonic energy in the bonding of microfluidic devices, and there are several remaining issues that have been overlooked. The surface condition before bonding is very crucial when ultrasonic vibration is applied on the bonding surfaces, because any undesirable surface asperities (such as surface unevenness and contamination
particles) can localize the ultrasonic energy as micro energy directors and melt instantly resulting in bonding failures. This engineering issue has been ignored in previous research. It is known that high bond strength and low loss in microchannel dimensional integrity are commonly controversial in direct thermal bonding process. When ultrasonic energy was introduced, it was reported that superior bonding with higher bond strength and little microchannel deformation could be obtained. However, these phenomena are still in lack of sufficient supporting experiments and studies, such as the effect of ultrasonic on the temperature variation of intimate contacting interface, and the effect of ultrasonic on thermal properties of polymeric substrate.

![Figure 2-16](image)

**Figure 2-16** (a) Schematic diagram of thermal-ultrasonic bonding system [167] and (b) photo of 12-layer chip bonded by thermal-ultrasonic bonding method [169].

### 2.4.5 Surface modifications

Despite of the attractive advantage of polymer homogeneity, direct thermal bonding cannot achieve bond strength comparable to adhesive bonding and solvent bonding because bond cannot be easily developed between surfaces with low surface free energies. In thermal bonding, the applied polymers especially
thermoplastics exhibit inert and hydrophobic surfaces, which may lead to several problems. Hydrophobic polymer surfaces are difficult to directly bond to adhesives, coatings, printing inks, etc. Hydrophobic surfaces can easily adsorb biological molecules such as proteins on the surfaces and lead to blockage of microchannels, which are undesirable in biomedical microfluidic applications. Moreover, external pumping is needed for highly hydrophobic microchannels where fluids are difficult to pass through. Therefore, it is necessary to modify the polymer surfaces prior to thermal bonding, in order to improve the surface energy and wettability.

2.4.5.1 Plasma treatment

Plasma, usually known as the fourth state of matter, is an electrically neutral medium of positive and negative particles, ions and electrons rather than neutral atoms or molecules [171]. The most commonly used plasma sources are direct current (DC) glow discharge and radio frequency (RF) power. Many reacting gases, such as oxygen, nitrogen, argon, hydrogen, carbon dioxide and fluorine, are employed to offer the unique surface properties on various polymers. Oxygen is probably the most preferred gas for polymer surface functionalization, wettability improvement and adhesion enhancement.

Oxygen plasma is not only extensively used for PDMS bonding and surface hydrophilization [172-174], but also applicable to those devices made in thermoplastics, such as PMMA [44, 133, 139, 175], COC/COP [139, 176-178], PC [179, 180], and PS [177]. Oxygen plasma treatment can generate polar functional
groups that can form hydrogen or covalent bonds across the interface which is capable of enhancing the bond strength. At the same time, oxygen plasma can also roughen the surface to improve the intimate contact between mating surfaces. However, the major problems of oxygen plasma treatment are that the functionalization is typically unstable, and either a partial or complete hydrophobic recovery is usually observed on the treated thermoplastics [181, 182]. The typical phenomenon of hydrophobic recovery in terms of contact angle on PMMA surface after oxygen plasma treatment is shown in Figure 2-17. The unstable modified surface with respect to time can cause the inconsistency of microchannel surface properties or even failure of microfluidic devices during the end applications. Therefore, there is a need to improve the stability and prolong the shelf-life of plasma modified surfaces by some additional treatments, such as chemical grafting and physical coating.

Figure 2-17  Hydrophobic recovery of PMMA plates after O₂ plasma treatment [181].
2.4.5.2 UV/O$_3$ treatments

An alternative to plasma treatment is the application of UV/O$_3$ to increase the surface energy of thermoplastic polymers. This method is capable of scissor long polymer molecules to decrease molecular weight resulting in the reduction of glass transition temperature of the treated thin layer while leaving the bulk polymer unaffected [183]. Figure 2-18 shows the nano-thermal analysis (nano-TA) results measured on PMMA surfaces treated by oxygen plasma, vacuum ultraviolet (VUV) and vacuum UV/O$_3$, which indicate that UV/O$_3$ treatment can produce the treated top nano-layer with lowest softening temperature [184]. UV/O$_3$ irradiation is applicable to bond PMMA [183-185], COC/COP [139, 176, 177] and PC [151] microfluidic devices at low temperature, therefore the integrity of microchannel can be retained. However, the functionalization in terms of hydrophilicity can also be largely lost upon DI water and commonly used solvents [139].

![Figure 2-18](image)

**Figure 2-18** Nano-TA results of PMMA surface with various treatments. The arrows indicate first softening point of treated samples [184].
2.4.5.3 Photografting

Photografting is a process to modify the polymer surface by covalent attachment of chemical groups to the polymer main chain through ultraviolet irradiation on monomer and photoinitiator mixture. Most of the monomers used are hydrophilic in nature, such as polyethylene glycol (PEG), acrylic acid (AA), Hydroxyethyl methacrylate (HEMA), which can significantly modify polymer surface with improved surface wettability and surface energy [186]. Lately, photografting has been applied on surface modification of microchannels and bonding of microfluidic devices. Photografting performed on very inert thermoplastic COC has proven to significantly reduce the protein adsorption [187, 188]. Similar photografting techniques were also investigated to improve the bond strength of COC microfluidic devices [189, 190]. However, in photografting process, both monomer and photoinitiator should be carefully prepared to be exposed under long-time ultraviolet irradiation. Moreover, some harsh solvents, such as acetone, used in photografting are not applicable to many thermoplastics with low chemical resistance, such as PMMA and PC.

2.4.5.4 Corona treatments

Another traditional method, corona discharge treatment also shows its potential in the surface modification of plastic parts, which uses discharge plasma to impact changes on the surface resulting in a more hydrophilic surface and then high bond strength [191-193]. However, corona discharge intensity is highly non-uniform over the treated surface as shown in Figure 2-19.
2.4.6 Summary

There are a number of considerations that should be taken into account when selecting and carrying out a proper bonding method.

(1) Bond strength:

Some microfluidic applications require high bond strength even close to cohesive strength of the bulk material. Some others need week or even reversible bonds.

(2) Bond interface properties:

Generally, homogeneous bond interface is required and suitable. Besides, it is better to retain or enhance desirable surface properties, such as surface energy, hydrophilicity, biocompatibility and chemical resistance.

(3) Microchannel dimensional integrity:

The shape of microchannel should be retained after bonding or maximum deformation should be kept within the acceptable limit.

Figure 2-19  Photo of corona discharge treatment on microfluidic substrate [192].
(4) Bondability (Manufacturability):

For each bonding method, the choice of material type (e.g. elastomers, thermoplastics), material properties (e.g. surface energy, wettability, and chemical property), semi-finished part form (e.g. film, thick plate), etc., should be considered.

(5) Productivity:

There is always a demand of low cost, rapid and high throughput bonding method of thermoplastic microfluidic devices. High productivity is required especially for hybrid bonding techniques, such as surface modification prior to thermal bonding.

Table 2-5 summarizes above reviewed bonding methods, including adhesive bonding, solvent bonding, thermal bonding, ultrasonic welding/bonding and surface modifications.
Table 2-5  Overview of bonding methods of thermoplastic microfluidic devices.

<table>
<thead>
<tr>
<th>Method</th>
<th>Typical thermoplastic</th>
<th>Bonding time</th>
<th>Bond strength</th>
<th>Process complexity</th>
<th>Cost</th>
<th>Mass production potential</th>
<th>Major intrinsic limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adhesive bonding</td>
<td>PMMA, COC, PC, PS, PET</td>
<td>Short - Medium</td>
<td>Medium - high</td>
<td>Low - medium</td>
<td>Low - medium</td>
<td>Medium</td>
<td>Microchannel clogging, Inhomogeneity of microchannel wall properties</td>
</tr>
<tr>
<td>Solvent bonding</td>
<td>PMMA, COC, PC</td>
<td>Short</td>
<td>High</td>
<td>Low - medium</td>
<td>Low</td>
<td>Medium - high</td>
<td>Solvent retention, Inhomogeneity of microchannel wall properties</td>
</tr>
<tr>
<td>Thermal bonding</td>
<td>PMMA, COC, COP, PC, PS</td>
<td>Long</td>
<td>Medium</td>
<td>Low</td>
<td>Low</td>
<td>Low - medium</td>
<td>Controversy of low microchannel deformation and high bond strength</td>
</tr>
<tr>
<td>Ultrasonic welding/bonding</td>
<td>PMMA, COC, PEEK</td>
<td>Short</td>
<td>Medium - high</td>
<td>Medium - high</td>
<td>Medium - high</td>
<td>High</td>
<td>Microchannel clogging, Complexity of design and mold fabrication, Difficulty in melting control</td>
</tr>
<tr>
<td>Surface modifications</td>
<td>PMMA, COC, COP, PC, PS</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium - high</td>
<td>Short lifetime (plasma), Instability of microchannel wall properties</td>
</tr>
</tbody>
</table>

1 Preparation time is not counted, such as applying adhesive, solvent, heating up, etc.
2 All the processes are taken into consideration including preparations before actual bonding process.
2.5 Proposed research scope

Based on above detailed review of microfluidic device fabrication, we have summarized the analysis results as shown in Figure 2-20.

This thesis focuses on three fabrication steps: tooling, replication and bonding. According to the summarized process selection criteria, micro hot embossing of bulk metallic glass micromold, micro injection molding of thermoplastic substrates and thermal bonding of thermoplastic substrates are selected, and the associated research objectives are targeted. Below is the detailed research scope of this thesis:
1. Fabrication of silicon micromold with predefined microfluidic patterns by photolithography and deep reactive-ion etching (DRIE), which can be used in the subsequent metallic micromold replication;

2. Fabrication of bulk metallic glass (BMG) micromold by thermoplastic-based micro hot embossing (μHE), which can be used in the subsequent thermoplastic substrate replication by micro injection molding (μIM);

3. Optimization of micro injection molding by design of experiment (DOE) to replicate high-fidelity microchannels into thermoplastic substrates with embossed BMG micromold;

4. Re-optimization of micro injection molding by design of experiment to reduce the molding-induced residual stresses, and investigation of the effects of residual stresses on microchannel deformation in thermal bonding;

5. Investigation and study of stable surface modifications, combining plasma treatment and low-$T_g$ polymer coating, in order to modify the inert surface of thermoplastics with higher surface energy and wettability, so that a low-temperature and deformation-free thermal bonding with sufficient bond strength can be performed;

6. Investigation and study of the effects of applied ultrasonic actuation on bonding temperature, in order to increase the interfacial temperature while keeping the bulk temperature as low as possible, so that the bond strength can be developed faster at the interface while the microchannels can be kept from undesired deformation.
The following research roadmap (see Figure 2-21) shows the flow of proposed research.

Figure 2-21  Research roadmap.
Chapter 3  Materials and Characterization

3.1 Materials

3.1.1 Micromold materials

The Silicon wafers used to fabricate the primary micromolds were purchased from Bonda Technology (Singapore). The specifications of the Si wafers are listed as below: 4”, diameter 100 ±0.2 μm, orientation <100> ±0.5°, thickness 525 ±25 μm, total thickness variation (TTV) <10 μm, P/B doped, resistivity 1-100 ohm/cm, single side polished, semi-standard flats, warpage <30 μm, and particles <20 @0.3μm.

Bulk metallic glasses are available in a wide range of chemical compositions with tunable mechanical, magnetic, chemical, and biological properties. In this research, the commercially available Zirconium-based BMG, LM0001B amorphous alloys, was purchased from Liquidmetal Technologies (USA) and used to fabricate the final micromolds. The Zr-based BMG contains five different elements: Zirconium, Titanium, Nickel, Copper and Beryllium. The pristine BMG plates were obtained in the square shape, with the dimension of 30 × 30 × 2.5 mm. They were grinded and polished with mirror finish prior to the fabrication of BMG micromold. The basic physical, mechanical and thermal properties supplied by the manufacturer are listed in Table 3-1.
### Table 3-1

Physical, mechanical and thermal properties of LM001B amorphous alloy [194].

<table>
<thead>
<tr>
<th>Item</th>
<th>LM001B</th>
<th>Unit/Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical properties</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td>6.1</td>
<td>g/cm³</td>
</tr>
<tr>
<td>Mechanical properties</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yield strength</td>
<td>1900</td>
<td>MPa</td>
</tr>
<tr>
<td>Hardness</td>
<td>550</td>
<td>Vickers</td>
</tr>
<tr>
<td>Impact strength</td>
<td>8</td>
<td>J/cm</td>
</tr>
<tr>
<td>Fracture toughness</td>
<td>55</td>
<td>MPa·m²</td>
</tr>
<tr>
<td>Elasticity</td>
<td>2.0</td>
<td>% original shape</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>93</td>
<td>GPa</td>
</tr>
<tr>
<td>Specific strength</td>
<td>311</td>
<td>kN·m/kg</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.39</td>
<td></td>
</tr>
<tr>
<td>Thermal properties</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal expansion</td>
<td>10.1</td>
<td>10⁻⁶ K⁻¹</td>
</tr>
<tr>
<td>Glass transition temperature</td>
<td>350-360</td>
<td>°C</td>
</tr>
<tr>
<td>Crystallization temperature</td>
<td>422</td>
<td>°C</td>
</tr>
<tr>
<td>Heat of crystallization</td>
<td>130</td>
<td>J/g</td>
</tr>
<tr>
<td>Melting onset temperature</td>
<td>667</td>
<td>°C</td>
</tr>
</tbody>
</table>

### 3.1.2 Substrate materials

The demand of commercializing microfluidic devices with a killer application has driven people to use thermoplastics such as PC, PMMA, COC and COP. Thermoplastics have been recognized as advantageous alternatives because they are relatively inexpensive and amenable to high volume production processes, such as micro injection molding, micro hot embossing and micro thermoforming.

In this present research, two commercially available thermoplastics, PMMA and COC were used. SUMIPEX® LG2 high-flow PMMA were purchased from Sumitomo Chemical (Japan) and TOPAS® 8007 COC were purchased from
Ticona (USA). Their physical, mechanical, optical and thermal properties are listed in Table 3-2.

Table 3-2  Physical, mechanical, optical and thermal properties of PMMA LG2 [195] and COC 8007 [196].

<table>
<thead>
<tr>
<th>Item</th>
<th>PMMA</th>
<th>COC</th>
<th>Unit/Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical properties</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water absorption</td>
<td>0.30</td>
<td>0.010</td>
<td>%</td>
</tr>
<tr>
<td>Water vapor transmission</td>
<td>–</td>
<td>0.0230</td>
<td>g/(m²·day)</td>
</tr>
<tr>
<td>Density</td>
<td>1.19</td>
<td>1.02</td>
<td>g/cm³</td>
</tr>
<tr>
<td>Mechanical properties</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tensile strength</td>
<td>68.0</td>
<td>63.0</td>
<td>MPa</td>
</tr>
<tr>
<td>Elongation at yield</td>
<td>7.0</td>
<td>4.5</td>
<td>%</td>
</tr>
<tr>
<td>Tensile modulus</td>
<td>3.10</td>
<td>2.60</td>
<td>GPa</td>
</tr>
<tr>
<td>Bending strength</td>
<td>110</td>
<td>–</td>
<td>MPa</td>
</tr>
<tr>
<td>Optical properties</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Refractive index</td>
<td>1.49</td>
<td>1.53</td>
<td></td>
</tr>
<tr>
<td>Transmission, visible</td>
<td>93</td>
<td>91</td>
<td>%</td>
</tr>
<tr>
<td>Thermal properties</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coefficient of linear expansion</td>
<td>$7 \times 10^{-5}$</td>
<td>$7 \times 10^{-5}$</td>
<td></td>
</tr>
<tr>
<td>Heat deflection temperature</td>
<td>90</td>
<td>68</td>
<td>°C</td>
</tr>
<tr>
<td>Glass transition temperature</td>
<td>100-105</td>
<td>80</td>
<td>°C</td>
</tr>
</tbody>
</table>
3.2 Characterization

3.2.1 Thermal gravimetric analysis (TGA)

Thermal gravimetric analysis was conducted to determine the degradation (or decomposition) temperatures of substrate thermoplastics. The TGA experiments were carried out on a TGA2950 thermogravimetric analyzer (TA Instruments, USA). The thermoplastic pellets with total weight of about 20 mg were spread uniformly in a Titanium pan. The temperature of the titanium pan in the furnace was equilibrated at 30°C and ramped to 500°C with a heating rate of 10°C/min. Then the temperature was elevated from 500°C to 600°C with a heating rate of 20°C/min. The onset point was recorded as the degradation temperature.

3.2.2 Differential scanning calorimetry (DSC)

Differential scanning calorimetry was conducted to determine the static glass transition temperatures of Zr-based BMG and substrate thermoplastics. The DSC experiments were carried out on a Q200 differential scanning calorimeter (TA Instruments, USA). Polymer pellets were pre-dried in an oven at temperature about 20 °C lower than the nominal $T_g$ for 4 hours to remove moisture, and cut into thinner sections in order to uniformly cover the Aluminum pan bottom. The temperature of the furnace was equilibrated at 30 °C and ramped to 20 °C above the expected $T_g$ with a heating rate of 20 °C/min. Then the sample was cooled down to 30 °C with a cooling rate of 30 °C/min. The second heating cycle was recorded. The inflection midpoint of the heat flow shift was recorded as the glass transition temperature.
3.2.3 Dynamic mechanical analysis (DMA)

Dynamic mechanical analysis was conducted to determine the dynamic thermal properties of the substrate thermoplastics. The DMA experiments were carried out on a Q800 dynamic mechanical analyzer (TA Instruments, USA) using single cantilever method. Plate samples were injection-molded and cut into strips with dimensions of around 25 mm × 10 mm × 1.5 mm. Single frequency test (1 Hz) and frequency sweep test (from 0.2 Hz to 20 Hz) were carried out with the temperature ranging from 35 °C to 100 °C. Each isothermal step took 5 min for every temperature increment of 5 °C. Storage modulus (E’), loss modulus (E’’), and Tan delta (Tan δ) were recorded. According to ASTM international standard designation E1640, the Tg shall be taken as the extrapolated onset to the sigmoidal change in storage modulus observed in going from the rigid region to the rubbery region of the thermoplastic being tested by DMA.

3.2.4 Fourier transform infrared (FTIR) spectroscopic analysis

Fourier transform infrared (FTIR) spectroscopy is an important analysis technique providing information about the chemical bonding or molecular structure of materials. It is an easy way to identify the presence of certain functional groups in a molecule, because molecular bonds and groups of bonds can vibrate at characteristic frequencies when the molecule is exposed to infrared rays. The chemical compounds of the PMMA surface before and after treatments were determined using a Perkin-Elmer GX Fourier transform infrared spectroscope by attenuated total reflection (ATR). The infrared beam passes
through the ATR crystal that it reflects at least once off the internal surface in contact with the sample. This technique enables direct measurement of samples without the need of special sample preparations. In this research, a total of 32 accumulation scans were carried out for each spectrum. The frequencies were reported in wavenumbers (cm$^{-1}$).

### 3.2.5 Contact angle measurement

Static contact angle on the thermoplastic surface were measured at room temperature by the sessile-drop mode using an optical tensiometer (Theta Attension, USA). A monochromatic cold led light source and a smooth lighting integrating sphere were used in this tensiometer to minimize undesirable sample evaporation. A 5 $\mu$L droplet of testing liquid was deposited on the sample surface. The static contact angle was calculated by the OneAttension software using Young-Laplace drop profile fitting method as shown in Figure 3-1, and the results were averaged from 10 readings (2 samples, 5 readings each).

![Figure 3-1](image)  
**Figure 3-1** Schematic diagram of contact angle measurement with a testing liquid on a solid surface.
3.2.6 Surface energy determination

Surface energy ($\gamma_{sv}$) was determined by the measured contact angles on sample surfaces, according to the Young’s equation (3-1) [197] shown below,

$$\gamma_{sv} = \gamma_{sl} + \gamma_{lv} \cos \theta + \pi_e$$  \hspace{1cm} (3-1)

where $\gamma_{sv}$ is the energy of the solid in contact with vapour, $\gamma_{sl}$ is the energy of the solid covered with liquid, and $\gamma_{lv}$ is the energy of the liquid-vapour interface, $\theta$ is the contact angle between solid and liquid, and $\pi_e$ is the equilibrium pressure of the adsorbed vapour on the solid which can be assumed to be zero. In order to calculate the surface energy $\gamma_{sv}$ from the contact angle, the second unknown variable $\gamma_{sl}$ in above equation must be determined. According to the Owens-Wendt-Rabel-Kaelble (OWRK) method, also known as the extended Fowkes method, the interfacial energy $\gamma_{sl}$ can be calculated based on the solid and the liquid surface energies and the interactions between the phases [198]. These interactions can be interpreted as the geometric mean of a dispersive component ($\gamma^d$) and a polar component ($\gamma^p$) of the surface energy, as shown in equations (3-2 to 3-5):

$$\gamma_{sv} = \gamma^d_{sv} + \gamma^p_{sv}$$  \hspace{1cm} (3-2)

$$\gamma_{lv} = \gamma^d_{lv} + \gamma^p_{lv}$$  \hspace{1cm} (3-3)

$$\gamma_{sl} = \gamma^d_{sl} + \gamma^p_{sl}$$  \hspace{1cm} (3-4)
\[ \gamma_{sd} = \gamma_{sv} + \gamma_{lv} - 2\sqrt{\gamma_{sv} \gamma_{lv}^d} - 2\sqrt{\gamma_{sv} \gamma_{lv}^p} . \]  \hspace{1cm} (3-5) \\

After combining equations (3-1 to 3-5), we can get \\

\[ \gamma_{lv} (1 + \cos \theta) = 2\sqrt{\gamma_{sv} \gamma_{lv}^d} + 2\sqrt{\gamma_{sv} \gamma_{lv}^p} . \]  \hspace{1cm} (3-6) \\

At least two liquids with known disperse and polar components of the surface energy are required to determine the solid surface energy. Therefore, \( \gamma_{sv}^d \) and \( \gamma_{sv}^p \) can be determined by measuring the contact angles of these liquids against the solid. In this chapter, DI water (H\(_2\)O) and ethylene glycol (C\(_2\)H\(_6\)O\(_2\)) were used to measure the contact angles.

### 3.2.7 Photoelastic stress analysis

In order to demonstrate the molded-in residual stress status, a modified Senarmont phase shift polariscope (see Figure 3-2) [199] was used to get a full-field measurement of phase retardation. In this system, a monochrome green light source was used to illuminate the sample. After passing through the linear polarizer and quarter wave plate, the light is circularly polarized and projected onto the molded PMMA substrate. When the light transmits through the substrate, different refractive indices can be generated along the orientations of two principal stress (\( \sigma_1 \), \( \sigma_2 \)) due to its photoelastic property, and the light exits elliptically polarized. Upon going through the rotating analyzer, the light is then captured by a CCD camera as phase shifted images at analyzing orientations of
0°, 45°, 90° and 135° respectively. The extraction of quantitative information then can be done in light intensity.

![Phase shift polariscope used in this study.](image)

**Figure 3-2** Phase shift polariscope used in this study.

The intensity of transmitted light is given as,

\[
I = \frac{A^2}{2} [1 + \sin \Delta \sin 2(\alpha - \beta)]
\]  

(3-7)

where, \(A\) is the amplitude of the circularly polarized light, \(\alpha\) is the angular position of the rotating analyzer, \(\beta\) is the direction of the first principal stress (fast axis) of the sample, and \(\Delta\) is the phase retardation lagged between fast and slow axes according to the stress-optic law.

\[
\frac{\Delta}{2\pi} = (\sigma_1 - \sigma_2) \frac{Cd}{\lambda}
\]  

(3-8)
where, \( C \) is the stress optic coefficient of the material, \( d \) is the sample thickness, and \( \lambda \) is the light wavelength. After four phase shifting images have been recorded, the intensity can be rewritten as,

\[
I_1 = I_a (1 - \sin \Delta \sin 2\beta) \quad (3-9)
\]

\[
I_2 = I_a (1 + \sin \Delta \cos 2\beta) \quad (3-10)
\]

\[
I_3 = I_a (1 + \sin \Delta \sin 2\beta) \quad (3-11)
\]

\[
I_4 = I_a (1 - \sin \Delta \cos 2\beta) \quad (3-12)
\]

\[
I_a = \frac{1}{4} (I_1 + I_2 + I_3 + I_4) \quad (3-13)
\]

where, \( I_a \) is the average light intensity and assumed to be constant during the experiment.

The phase retardation and the direction of the first principal stress can be deduced as,

\[
\Delta = \sin^{-1} \left\{ \frac{2[(I_3 - I_4)^2 + (I_4 - I_2)^2]^{1/2}}{I_1 + I_2 + I_3 + I_4} \right\} \quad (3-14)
\]

\[
\beta = \frac{1}{2} \tan^{-1} \left( \frac{I_1 - I_3}{I_4 - I_2} \right) \quad (3-15)
\]

According to the stress-optical law, when the polarized light passes through the stressed material, phase retardation is produced and proportional to the principal stress difference, which in this case is derived from the molded-in
residual stress. In this chapter, four phase shift images for each testing sample were captured by camera and processed by MATLAB program to determine the principal-stress direction and the phase retardation [200]. Then the stress status in the molded substrates can be analyzed in terms of phase retardation.

### 3.2.8 Confocal profilometry

In contrary to widefield images, confocal images contain optical section information, which is rich in detail and potential for three-dimensional (3D) visualization of microscopic features. These confocal images can be obtained by illuminating and observing a single diffraction limited spot, which requires two beam segments to concur in their focus, as shown in Figure 3-3. In this present thesis, the 3D topography and 2D profile measurements were performed using a polarized light micro (PLμ) confocal profilometer (Sensofar, USA), in order to determine the dimension of microstructures, morphology and surface roughness.

![Schematic diagram of working principle of confocal profilometer.](image-url)
3.2.9 Bond strength measurement

Bond strength was evaluated by lap shear test (as shown in Figure 3-4) on an Instron testing machine. For each measurement, a pair of substrates with overlapping area of 25 mm × 25 mm was bonded and at least three chips were tested at room temperature. Before testing, compensative plates (25 mm × 25 mm) were adhered to the bonded chip by Araldite epoxy adhesive to avoid the misalignment issue during the test. The distance between upper and lower grips was kept constant and the crosshead moving speed of 0.5mm/min was applied for each test. The bond strength was calculated as the maximum failure load divided by the overlapping area (25 mm × 25 mm) of each bonded sample.

![Figure 3-4](image.png)

**Figure 3-4**  Schematic diagrams of bond strength test: (a) adhesion of compensative (supporting) plates onto bonded chip, (b) longitudinal cross-sectional view of bonding section and (b) lap shear test on tensile testing machine.
Chapter 4  High-fidelity Replication  
using BMG Micromold

4.1 Introduction

In this chapter, the fabrication process from the micromold fabrication to the microfluidic substrate replication by micro injection molding is presented. A universal platform substrate was designed and fabricated in our work, which made it highly flexible to fabricate microfluidic devices with different designs and convenient to enable the chip-to-world interconnection with easy tubing connection. Several specific molding tools with easy replacement of micromold were used to fabricate two types of microfluidic substrates, the platform substrates and the plain flat substrates. Si primary micromold was fabricated using photolithography and deep reactive-ion etching (DRIE) technologies. A more robust material, bulk metallic glass (BMG) was used to fabricate the final micromold by micro hot embossing from the Si primary micromold. In order to replicate microfluidic features with high quality by micro injection molding with the embossed BMG micromold, the replication fidelity was studied through a Taguchi design of experiment method and the effects of processing parameters on replication fidelity were investigated.
4.2 Chip design and molding tools setup

4.2.1 Substrate and chip configuration

Flat polymeric plate is the most conventional and widely-used substrate for the fabrication of microfluidic devices. After microfluidic pattern transferring, the substrate needs to be bonded with a blank cover plate pre-drilled with several through holes as fluid inlets and outlets. This configuration typically comes with some drawbacks such as misalignment and time-consuming tubing interconnection. In contrast to above described configuration, a universal platform substrate was designed and fabricated in our work, as shown in Figure 4-1. The general design size of the platform substrate is 75 mm × 25 mm × 1.5 mm (length, width and thickness), equivalent to the size of a standard microscopy slide. Therefore, it is very easy and convenient to fix the platform substrate on the slide holder under the microscope. The platform substrate has 2 lines of 15 inlet/outlet ports at the long sides of the substrate, making it easy and rapid for tubing connection. It can be injection-molded as a patterned substrate (see Figure 4-2(a)) with microfluidic design or just a blank substrate (see Figure 4-2(b)). Various microfluidic patterns can be injection-molded onto the substrate just by replacing different micromolds in the micro injection molding system. It is also convenient to use the molded blank substrate for other alternative patterning methods, such as micro hot embossing. In an ideal situation, the microfluidic pattern can take full advantage of the inlet/outlet ports and the whole substrate area. However, due to the size limitation of the pristine BMG plate (30 mm × 30 mm × 2.5 mm) introduced in chapter 3, all the microfluidic patterns used in this thesis were
design within an area of 25 mm × 25 mm and replicated onto the middle portion of the substrates.

![Figure 4-1](image)

**Figure 4-1** Schematic diagram of (a) patterned platform substrate, (b) blank platform substrate.

In this thesis, a plain flat substrate without inlet/outlet ports was also injection-molded and used in order to assemble with the platform substrate, as shown in Figure 4-2(c), and either substrate can be replicated with the designed microfluidic pattern, as shown in Figure 4-2(d). Table 4-1 summarizes the two types of substrates fabricated in our work with typical examples. Though these substrates are versatile to various microfluidic designs, four microfluidic patterns were used in this thesis, as shown in Figure 4-3 and Table 4-2.

![Figure 4-2](image)

**Figure 4-2** Schematic diagram of (a) a bonded microfluidic device including a platform substrate and a plain substrate without ports, and (b) the cross-sectional views showing two types of chip configurations.
Table 4-1  Platform and plain substrates fabricated in this thesis.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Specification</th>
<th>Feature</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Platform</td>
<td>75 mm × 25 mm × 1.5 mm with inlet/outlet ports</td>
<td>Blank</td>
<td><img src="image1" alt="Blank Platform" /></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Patterned</td>
<td><img src="image2" alt="Patterned Platform" /></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Blank</td>
<td><img src="image3" alt="Blank Plain" /></td>
</tr>
<tr>
<td>Plain</td>
<td>75 mm × 25 mm × 1.5 mm</td>
<td>Patterned</td>
<td><img src="image4" alt="Patterned Plain" /></td>
</tr>
</tbody>
</table>

Figure 4-3  Microfluidic patterns used in this thesis (pattern #3 was designed by the researchers in Massachusetts Institute of Technology for collaborated Singapore-MIT Alliance program).
<table>
<thead>
<tr>
<th>Pattern</th>
<th>Function</th>
<th>Critical dimensions</th>
<th>Designed by</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>Droplet generation (multi-layer chip)</td>
<td>50 – 300 μm</td>
<td>Yu Hao</td>
</tr>
<tr>
<td>#2</td>
<td>Mixing</td>
<td>30 – 200 μm</td>
<td>Yu Hao</td>
</tr>
<tr>
<td>#3</td>
<td>Mixing</td>
<td>30 – 200 μm</td>
<td>MIT researchers [32]</td>
</tr>
<tr>
<td>#4</td>
<td>Droplet generation (double-layer chip)</td>
<td>200 μm</td>
<td>Chong Zhuangzhi</td>
</tr>
</tbody>
</table>

### 4.2.2 Molding tools

A Battenfeld HM25/60 injection molding machine was used in this chapter. Dedicated molding tools, as shown in Figure 4-4, were designed with centralized clamping device to mount micromold, in order to fabricate substrates with various microfluidic designs. Each micromold with the footprint size of 25 mm × 25 mm can be mounted in the mold core, resulting in molded 75 mm × 25 mm substrate with microfluidic patterns located at the center.

![Molds](image-url)

**Figure 4-4** (a) Injection molds for platform substrate and (b) injection molds for plain substrate. Dashed-line squares indicate the positions in the molds where the embossed BMG micromold can be mounted.
4.3 Fabrication of micromold

4.3.1 Si primary micromold

The fabrication process of Si micromold is illustrated in Figure 4-5.

A single polished <100>-type Silicon wafer was carefully cleaned by immersion in a 96% v/v H$_2$SO$_4$ solution at 120 °C for 20 min to remove any organic matters on the wafer surface, followed by deionized (DI) water flushing and spin-drying. In order to obtain good adhesion between photoresist and Si wafer, a thin layer of hexamethyldisilazane (HDMS) primer was coated onto the wafer surface by vapor deposition at 100 °C. A layer of 2-6 μm thick AZ9260 positive photoresist (MicroChemicals GmbH) was deposited onto the silicon wafer with optimized spin-coating recipe. Then it was soft-backed at 100 °C for 4
min on a hotplate and rehydrated at room temperature for about 5 min. Microfluidic design was pre-patterned on a chrome-coated glass or a plastic transparency, which was used as the mask in the ultraviolet (UV) exposure process. The photoresist was exposed under 365 nm UV light for 30-45 s with an exposure intensity of about 9.3 mW/cm². Then the exposed photoresist was developed in a diluted AZ 400K developer solution for 2 min and flushed by DI water.

A standard deep reactive-ion etching (DRIE) process was then applied on the photo-patterned wafer to etch the silicon with desired microchannel depth. The remaining AZ9260 photoresist can protect the beneath silicon from ion etching, while the exposed silicon can be etched as microchannels. The radio frequency (RF) power was kept constant at 800 W. For each etching/passivation cycle, the time of etching using SF₆ and O₂ gases and passivation using C₄F₈ gas was optimized to be 8 s and 10 s, respectively. The DRIE total etching time and number of etching cycles were determined by the designed microchannel depth and the pattern area.

4.3.2 BMG micromold

After DRIE, the silicon wafer was cut to small pieces of silicon primary micromold. Micro hot embossing, a typical method of thermoplastic forming technology, was used to replicate microstructures from the Si primary micromold to a more robust Zr-based bulk metallic glass (BMG) micromold. The micro hot embossing experiments were carried out on an Instron testing machine with
custom-made heating platens and temperature control unit, as shown in Figure 4-6.

![Micro hot embossing apparatus used to fabricate BMG micromold.](image)

**Figure 4-6** Micro hot embossing apparatus used to fabricate BMG micromold.

The fabrication process of BMG micromold is illustrated in Figure 4-7. A pair of a silicon primary micromold and a BMG plate was placed between the platens with an initial low pressure ($P_o$) to ensure sufficient contact between silicon and BMG, which were gradually heated up to the embossing temperature ($T_e$) slightly higher than the glass transition temperature ($T_g$) of BMG. When embossing temperature was reached, the compression pressure was increased till the target value ($P_e$) and it was held for very short duration, about 2 min, to avoid unexpected crystallization of the amorphous alloy. After the embossing pressure was released, the bonded BMG plate and silicon micromold were removed together from the platens and cooled naturally at room temperature (RT). The BMG plate was then separated from the silicon micromold by etching away the silicon in a 30% w/v Potassium hydroxide (KOH) solution at 80 °C ($T_s$) with
stirring for 30 min, exposing the embossed BMG microstructures. In order to make the embossed BMG plate compatible with the micro injection molding tools, the BMG plate was wire-cut to square micromold with a footprint size of 25 mm × 25 mm.

![Figure 4-7 Schematic diagram of BMG micromold fabrication process: (a) heating Si primary micromold and BMG plate to above the T_g of BMG with initial low pressure P_o, (b) compression with increasing pressure till target value P_e at embossing temperature T_e, (c) removal of Si in KOH solution at T_s, and (d) post-processing of BMG micromold to make it compatible with micro injection molding machine.](image)

4.3.3 Results and discussion

4.2.3.1 Si primary micromold

The DRIE of Si wafer can produce Si microchannel sidewalls with taper angle of less than 2°, as shown in Figure 4-8. Though vertical microchannel sidewalls are highly desired in microfluidic experiments and simulations, a tapered sidewall is
advantageous in easy demolding of molded polymer substrate from micromold during micro injection molding and micro hot embossing.

![Figure 4-8](image)

**Figure 4-8** (a) 3D topography and (b) 2D profile plot of a 25 μm wide and 21 μm deep microchannel on a Si micromold after DRIE showing the sidewall taper angle of about 1.8°.

Another phenomenon associated with DRIE of Si is sidewall scalloping. The working principle of DRIE etching and passivation processes is illustrated in Figure 4-9(a). The protective chemical C₄F₈ is deposited on the sidewalls as well as the bottom of microchannels, but the anisotropic etching removes the layer at the bottom faster than that on the sidewalls. Due to the repetition of etching/passivation cycles, the sidewalls can not be perfectly smooth, where the scallop microstructures are generated. As shown in Figure 4-9(b), the obtained pitch between scallop microstructures was about 0.66 μm.
4.2.3.2 BMG micromold

The glass transition temperature was determined to be about 360 °C as shown in Figure 4-10, measured by DSC at constant heating rate of 20 °C/min. The typical thermal history of BMG during the micro hot embossing process is demonstrated in Figure 4-11. The temperature was elevated from the room temperature to 380 °C (20 °C higher than \( T_g \)) and kept constant during embossing process. Figure 4-11 also shows the typical profile of applied pressure. An initial compression pressure of about 1 MPa during heating was necessary to ensure the intimate contact and thermal conduction between BMG plate and Si primary micromold. The target embossing pressure (10 to 40 MPa) used in this chapter depended on
the critical dimension of microstructures ranging from 500 μm to 20 μm (the minimum critical dimension provided by the plastic transparency mask.)

**Figure 4-10**  DSC curve of measured $T_g$ of the Zr-based bulk metallic glass.

**Figure 4-11**  Schematic diagram of typical temperature and compression pressure profiles used in the micro hot embossing process.
Figure 4-12 and Figure 4-13 show SEM micrographs of the microfluidic features produced on the Si primary micromold by DRIE and the resulting features replicated on the BMG micromold by micro hot embossing.

**Figure 4-12** SEM micrographs of microchannels (pattern #1) on Si primary micromold (left) and embossed inverted microchannels on BMG micromold (right).

**Figure 4-13** SEM micrographs of inverted microchannels (pattern #2) on Si primary micromold (left) and embossed microchannels on BMG micromold (right).
It also should be noted that the scallop microstructures produced on the microchannel sidewalls during DRIE process were also replicated onto the BMG micromold as shown in Figure 4-14. In the figure, the colored circles, squares and triangles present the mating surfaces on Si micromold and BMG micromold during embossing. By applying the optimized DRIE process, the obtained pitch between scallop microstructures was about 0.8 μm, which was acceptable in the following BMG micromold fabrication and negligibly affected the demolding in micro injection molding.

![Figure 4-14](image)

Figure 4-14   Replication of sidewall scalloping and surface roughness from Si primary micromold (left) to embossed BMG micromold (right). Colored circles, squares and triangles highlight the mating surfaces in micro hot embossing.

4.4 Replication of microchannels

4.4.1 Optimization methodology

In the fabrication of microfluidic substrates, good microchannel replication fidelity is highly desired, which can affect the consistency of the final microfluidic application. Therefore, the replication process of microchannels should be optimized with carefully conducted design of experiment (DOE). The
Dimension variance of the microchannel replicated from the micromold should be controlled as small as possible. The designed spacing between each two microchannels on the micromold is ten folds of the designed microchannel width. Incomplete filling can happen when the polymer melt flows into the microcavities (spaces between inverted microchannels), which can lead to a wider microchannel. Compared to the width, the depth of microchannel could be easily molded with good fidelity as shown in Figure 4-15(a). The microchannels shown in Figure 4-15(b) were replicated with fillets due to incomplete filling caused by improper molding conditions. These defects indicate that it was more necessary to improve the replication fidelity of microchannel width in this case; therefore, here we only considered the width as the response in the Taguchi L18 orthogonal array.

![Figure 4-15](image)

Figure 4-15  (a) Schematic diagram of incomplete filling of microcavity and (b) SEM micrographs of replicated microchannels due to incomplete filling (left: U-turn microchannel, middle: straight microchannel, and right: Y-junction).
Figure 4-16 shows the SEM micrographs of inverted microchannels on the embossed BMG micromold and measured cross-sectional profiles. The width and depth were 54.1 \( \mu \text{m} \) and 40.7 \( \mu \text{m} \), respectively. As the sidewall of microstructure was not vertical as shown in Figure 4-16(c), it was inaccurate to measure the width manually with the confocal PL\( \mu \) analysis software. Therefore, Sobel filter operation, which is a widely used method for edge detection in imaging processing, was applied based on the measured cross-sectional profiles. The processed result after Sobel operation is illustrated in Figure 4-16(d). After post-processing, the original sidewalls can be represented by a peak and a valley. Thus it was more convenient to measure the distance between the peak and the valley projected on X axis, which can be considered as the equivalent width on the midline in the original profile.

Figure 4-16  (a-b) SEM micrographs of inverted microchannels on the BMG micromold, (c) typical microchannel profile on the BMG micromold and (d) processed result using Sobel filter operation for measurement of the equivalent width.
In order to study the effects of processing parameters on the replication fidelity of micro injection molding, a fractional factorial Taguchi experiment was designed. The philosophy of Taguchi method is to place effort into reducing variation in response at source. Meanwhile, a reliable Taguchi design can be achieved by analyzing an evaluation measure called signal-to-noise (S/N) ratio. The best replication quality can be obtained by maximizing the signal-to-noise ratio. Considering the principle and characteristic of micro injection molding, the width of molded microchannel was expected to be larger than the target width of mold insert. Therefore, the quantity characteristic “smaller-the-better” was chosen to calculate the S/N ratio. The calculation formula is shown as below:

\[
S/N = -10 \log \left( \sum_{i=1}^{n} \frac{y_i^2}{n} \right)
\]  

(4-1)

where \( n \) is the number of measurements and \( y_i \) is the individual measurement result. In addition to the Taguchi method, analysis-of-variance (ANOVA) was also conducted in order to evaluate the effect significance for each processing parameter on the replication fidelity.

In the design of experiment, PMMA LG2 was used as the substrate material. Eight processing parameters in micro injection molding were selected, including pre-drying (A), melt temperature (B), mold temperature (C), injection volume flow (D), injection pressure (E), holding pressure (F), holding time (G) and cooling time (H). For factor A, two levels were defined, while for the rest seven factors, three levels were considered respectively, as listed in Table 4-3. The
selected level values were determined on the basis of recommended processing conditions by the material manufacturer and our previous trial-and-error experiments. All the other environmental and operational conditions were considered as uncontrollable and treated as noise factors. Furthermore, the interactions of any two independent parameters were accounted negligible in this Taguchi design.

Table 4-3  Micro injection molding processing parameters and selected levels in the Taguchi method.

<table>
<thead>
<tr>
<th>Processing parameters (factors)</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L1</td>
</tr>
<tr>
<td>A Pre-drying (@70°C for 4 hours)</td>
<td>Yes</td>
</tr>
<tr>
<td>B Melt Temperature (°C)</td>
<td>220</td>
</tr>
<tr>
<td>C Mold Temperature (°C)</td>
<td>65</td>
</tr>
<tr>
<td>D Injection Volume Flow (ccm/s)</td>
<td>18</td>
</tr>
<tr>
<td>E Injection Pressure (bar)</td>
<td>700</td>
</tr>
<tr>
<td>F Holding Pressure (bar)</td>
<td>480</td>
</tr>
<tr>
<td>G Holding Time (s)</td>
<td>4</td>
</tr>
<tr>
<td>H Cooling Time (s)</td>
<td>15</td>
</tr>
</tbody>
</table>

The total degree of freedom (DOF) of Taguchi array was calculated as 1 + 2 × 7 = 15. According to the prerequisite of Taguchi method, the number of experimental runs should not be less than the total degree of freedom of the Taguchi array; therefore, a level-mixed Taguchi method L18 orthogonal array ($2^1 \times 3^7$) was designed as shown in Table 4-4. The design runs from 1 to 18 was randomized to get the factual experimental run sequence. For each experimental run in the Taguchi method, 15 replicas were produced by micro injection
molding with the embossed BMG micromold (pattern #3), but only the last 5 replicas were measured in order to reduce the experimental error under a relative stable working condition. Microfluidic pattern #3 was chosen as the study objective because it had smaller microchannel dimensions compared with other patterns. On each replicated substrate, the microchannel profiles were measured at a predetermined position as shown in Figure 4-17. All the measurements were conducted using the confocal profilometer.

Table 4-4  Experimental runs of Taguchi L18 orthogonal array.

<table>
<thead>
<tr>
<th>Design run</th>
<th>Factual run</th>
<th>Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>A B C D E F G H</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>L1 L1 L1 L1 L1 L1 L1 L1</td>
</tr>
<tr>
<td>2</td>
<td>12</td>
<td>L1 L1 L2 L2 L2 L2 L2 L2</td>
</tr>
<tr>
<td>3</td>
<td>18</td>
<td>L1 L1 L3 L3 L3 L3 L3 L3</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>L1 L2 L1 L1 L2 L2 L3 L3</td>
</tr>
<tr>
<td>5</td>
<td>11</td>
<td>L1 L2 L2 L2 L3 L3 L1 L1</td>
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<td>10</td>
<td>L1 L2 L3 L3 L1 L1 L2 L2</td>
</tr>
<tr>
<td>7</td>
<td>8</td>
<td>L1 L3 L1 L2 L1 L3 L2 L3</td>
</tr>
<tr>
<td>8</td>
<td>4</td>
<td>L1 L3 L2 L3 L2 L1 L3 L1</td>
</tr>
<tr>
<td>9</td>
<td>16</td>
<td>L1 L3 L3 L1 L3 L2 L1 L2</td>
</tr>
<tr>
<td>10</td>
<td>6</td>
<td>L2 L1 L1 L3 L3 L2 L2 L1</td>
</tr>
<tr>
<td>11</td>
<td>3</td>
<td>L2 L1 L2 L1 L1 L3 L3 L2</td>
</tr>
<tr>
<td>12</td>
<td>17</td>
<td>L2 L1 L3 L2 L2 L1 L1 L3</td>
</tr>
<tr>
<td>13</td>
<td>9</td>
<td>L2 L2 L1 L2 L3 L1 L3 L2</td>
</tr>
<tr>
<td>14</td>
<td>13</td>
<td>L2 L2 L2 L3 L1 L2 L1 L3</td>
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<td>15</td>
<td>14</td>
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</tr>
<tr>
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<td>7</td>
<td>L2 L3 L2 L1 L3 L1 L2 L3</td>
</tr>
<tr>
<td>18</td>
<td>1</td>
<td>L2 L3 L3 L2 L1 L2 L3 L1</td>
</tr>
</tbody>
</table>
4.4.2 Results and discussion

After Sobel filter operation, the measured equivalent width values of microchannels are listed in Table 4-5.

After calculating the S/N ratio for each experimental run, the averaged S/N ratio can be determined for each specific factor and level. The S/N ratio plots of main effects are shown in Figure 4-18, where the difference between the highest S/N and lowest S/N was calculated as S/N delta.
Table 4-5  Measurement results of equivalent width of molded microchannels.

<table>
<thead>
<tr>
<th>Design run</th>
<th>Factual run</th>
<th>Response observations: equivalent width of microchannels (μm)</th>
<th>Average (μm)</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>60.38 58.88 60.38 60.00 59.62</td>
<td>59.85</td>
<td>± 0.56</td>
</tr>
<tr>
<td>2</td>
<td>12</td>
<td>56.25 56.62 54.38 57.00 56.62</td>
<td>56.17</td>
<td>± 0.93</td>
</tr>
<tr>
<td>3</td>
<td>18</td>
<td>54.38 55.12 55.88 55.50 53.62</td>
<td>54.90</td>
<td>± 0.81</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>53.25 54.75 56.25 56.62 56.62</td>
<td>55.50</td>
<td>± 1.32</td>
</tr>
<tr>
<td>5</td>
<td>11</td>
<td>54.75 54.75 54.75 55.12 54.38</td>
<td>54.75</td>
<td>± 0.23</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>55.50 54.38 55.12 54.75 54.75</td>
<td>54.90</td>
<td>± 0.38</td>
</tr>
<tr>
<td>7</td>
<td>8</td>
<td>54.38 54.38 53.25 54.75 51.38</td>
<td>53.63</td>
<td>± 1.23</td>
</tr>
<tr>
<td>8</td>
<td>4</td>
<td>54.00 55.12 54.00 53.25 53.62</td>
<td>54.00</td>
<td>± 0.63</td>
</tr>
<tr>
<td>9</td>
<td>16</td>
<td>51.38 55.12 54.75 53.62 54.75</td>
<td>53.92</td>
<td>± 1.37</td>
</tr>
<tr>
<td>10</td>
<td>6</td>
<td>58.12 55.50 54.00 57.70 56.25</td>
<td>56.31</td>
<td>± 1.50</td>
</tr>
<tr>
<td>11</td>
<td>3</td>
<td>61.88 62.25 60.75 62.62 62.25</td>
<td>61.95</td>
<td>± 0.64</td>
</tr>
<tr>
<td>12</td>
<td>17</td>
<td>55.88 57.75 57.75 57.75 58.12</td>
<td>57.45</td>
<td>± 0.80</td>
</tr>
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<td>13</td>
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<td>56.10</td>
<td>± 0.77</td>
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<td>15</td>
<td>14</td>
<td>55.88 55.88 53.25 55.12 54.38</td>
<td>54.90</td>
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<td>16</td>
<td>15</td>
<td>56.62 54.38 55.50 55.50 55.50</td>
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<td>± 0.71</td>
</tr>
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<td>55.88 55.50 55.50 55.88 56.25</td>
<td>55.80</td>
<td>± 0.28</td>
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<tr>
<td>18</td>
<td>1</td>
<td>55.12 54.75 55.12 55.12 54.38</td>
<td>54.90</td>
<td>± 0.30</td>
</tr>
</tbody>
</table>
Figure 4-18  Main effect plots of S/N ratios for all the processing parameters (factors).
Moreover, the main effects for mean width were also considered in addition to S/N ratios, in order to identify the main factors that affect the mean response (width) but not the variance. The calculated values of S/N ratio delta and mean width delta are listed in Table 4-6. The mean width delta was defined as the difference between the highest mean width and the lowest mean width for each factor. The ranking results showed that the effect analysis based on mean width agreed well with the effect analysis based on S/N ratio. The only difference in the ranking of factor A and factor C indicated that the mean effect was slightly dominant by factor C while the variance effect was slightly dominant by factor A. In the Taguchi analysis, the highest S/N ratio or the smallest mean width indicated the optimal processing condition for each factor; therefore, the optimal combination of factors could be concluded as follows: pre-drying (A1: Yes), melt temperature (B3: 260°C), mold temperature (C3: 75°C), injection volume flow (D3: 32 ccm/s), injection pressure (E3: 1000 bar), holding pressure (F2: 580 bar), holding time (G2: 8 s) and cooling time (H3: 25 s).

<table>
<thead>
<tr>
<th>Analysis method</th>
<th>Factors</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>S/N Delta</td>
<td>A1-A2</td>
<td>0.197</td>
<td>B3-B1</td>
<td>0.480</td>
<td>C3-C2</td>
<td>0.195</td>
<td>D3-D1</td>
<td>0.254</td>
<td>E3-E1</td>
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<td>2</td>
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<td>8</td>
<td></td>
</tr>
<tr>
<td>Mean width Delta</td>
<td>A2-A1</td>
<td>1.274</td>
<td>B1-B3</td>
<td>3.148</td>
<td>C2-C3</td>
<td>1.300</td>
<td>D1-D3</td>
<td>1.703</td>
<td>E1-E3</td>
</tr>
<tr>
<td>Rank</td>
<td>5</td>
<td>1</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>7</td>
<td>6</td>
<td>8</td>
<td></td>
</tr>
</tbody>
</table>
Based on above mean width calculated in Taguchi method, ANOVA table for mean width was determined (see Table 4-7). From the viewpoint of P-value, only factor B (melt temperature) had significant effect on the width replication fidelity at the confidence of 95% level, because its P-value (0.0243) was smaller than the probability level at 0.05. Results also showed that only the F-value of factor B was larger than $F_{0.05,2,2} = 19.0$ while all the other F-values were smaller than their corresponding critical F-values, which indicated that factor B (melt temperature) was the most significantly effective parameter selected in this experimental design. It agreed well with the ranking results concluded from previous Taguchi method for both S/N and mean analysis.

Table 4-7  
ANOVA result for mean response ($F_{0.05,1,2} = 18.5128$ and $F_{0.05,2,2} = 19.0$ obtained from F-distribution table with probability level $\alpha = 0.05$).

<table>
<thead>
<tr>
<th>Sources</th>
<th>DOF</th>
<th>Sum of squares</th>
<th>Mean squares</th>
<th>F-value</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>A  Pre-drying (@70°C for 4 hours)</td>
<td>1</td>
<td>7.3064</td>
<td>7.3064</td>
<td>18.1525</td>
<td>0.0509</td>
</tr>
<tr>
<td>B  Melt Temperature (°C)</td>
<td>2</td>
<td>32.3701</td>
<td>16.1851</td>
<td><strong>40.2113</strong></td>
<td><strong>0.0243</strong></td>
</tr>
<tr>
<td>C  Mold Temperature (°C)</td>
<td>2</td>
<td>5.5572</td>
<td>2.7786</td>
<td>6.9034</td>
<td>0.1265</td>
</tr>
<tr>
<td>D  Injection Volume Flow (ccm/s)</td>
<td>2</td>
<td>10.2547</td>
<td>5.1274</td>
<td>12.7388</td>
<td>0.0728</td>
</tr>
<tr>
<td>E  Injection Pressure (bar)</td>
<td>2</td>
<td>8.5114</td>
<td>4.2557</td>
<td>10.5732</td>
<td>0.0864</td>
</tr>
<tr>
<td>F  Holding Pressure (bar)</td>
<td>2</td>
<td>2.3152</td>
<td>1.1576</td>
<td>2.8761</td>
<td>0.2580</td>
</tr>
<tr>
<td>G  Holding Time (s)</td>
<td>2</td>
<td>3.7115</td>
<td>1.8558</td>
<td>4.6106</td>
<td>0.1782</td>
</tr>
<tr>
<td>H  Cooling Time (s)</td>
<td>2</td>
<td>2.4774</td>
<td>1.2387</td>
<td>3.0775</td>
<td>0.2452</td>
</tr>
<tr>
<td>Residual</td>
<td>2</td>
<td>0.8050</td>
<td>0.4025</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>17</td>
<td>73.3090</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Validation tests were conducted with the obtained optimal parameter combination. The PMMA pellets were pre-dried before micro injection molding and the other parameters were set at melt temperature 260°C, mold temperature 75°C, injection volume flow 32 ccm/s, injection pressure 1000 bar, holding pressure 580 bar, holding time 8 s and cooling time 25 s. The measured width and depth of microchannel in the validation test were 54.3 μm and 40.9 μm, with percent error of 0.44% and 0.46%, respectively. SEM micrographs of some replicated samples are shown in Figure 4-19.

![SEM micrographs](image)

**Figure 4-19** SEM micrographs of the microchannels (pattern #3) replicated from the BMG micromold (left) onto the PMMA plain substrate (right) using the optimal processing conditions.

With above successful optimization on replication fidelity of microchannels, the replication of various microstructures with different geometries and dimensions can also be optimized using the similar procedure of
Taguchi analysis. Figure 4-20 shows some other replicated microchannels, which were used for different microfluidic applications.

Figure 4-20 SEM micrographs of the microchannels replicated from the BMG micromold (left) onto the PMMA substrates (right) using the optimal processing conditions obtained from Taguchi optimization methods. (a) 250 μm wide microchannels on a double emulsion generation substrate (pattern #1), (b) 200 μm wide microchannels on a single droplet generation substrate (pattern #4)
Chapter 5  Molding Optimization with Reduced Residual Stresses

5.1 Introduction

There are many reported works on optimization of micro injection molding process for high-fidelity replication [121-124]. By applying appropriate processing parameters, microchannel geometry can be replicated with great accuracy; however, some undesirable stress, such as flow-induced and thermally-induced residual stresses, may also be created at the same time [117, 201]. The analysis of such molded-in stresses and their potential impact on further back-end process, i.e. sealing of microchannels, has hitherto been ignored.

Among all existing bonding methods, direct thermal bonding is advantageous in simplicity and material homogeneity. However, the applied compression force and heating cycle can lead to the deformation of replicated microchannels [51]. Therefore, several surface treatment methods have been utilized to improve the wettability of materials before thermal bonding [139, 175, 177, 202]. These methods enhance the interfacial bond strength while maintaining the microchannel integrity. But these treatment methods may also affect the material homogeneity and cause unstable surface properties resulting in inconsistent performance during device operation. Numerical simulation and
modeling have also been proposed to assess microchannel deformation and to establish optimal thermal bonding conditions [203].

In direct thermal bonding process, irregular microchannel deformation can either be caused by heterogeneity in bonding load distribution, or be attributed to the residual stress induced by high temperature microfabrication process, e.g., micro injection molding [141], even though good microchannel fidelity has already been achieved. Usually, the molded-in residual stresses can be developed during filling, holding and cooling in the mold cavity [201]. However, to the best of our knowledge, there is no investigation done on the influence of molded-in residual stress on surface region in terms of microchannel integrity during widely-used direct thermal bonding process. In fact, this issue is important, particularly to the operation of thermoplastic microfluidics, because high internal stress can be developed near the surface regions in molded part [204], which may result in anisotropy of optical properties, long-term dimensional instability [117], viscoelastic deformation [118], residual tensile stress induced cracking (e.g. crazing) [119], and high sensitivity to chemical diffusion [120].

If the molded-in residual stress can be qualitatively assessed or quantitatively measured, corresponding actions can be taken to control the fabrication process and eliminate the potential negative effects. For macro molded plastic parts, there are several destructive testing (DT) methods to determine the residual stress in molded products, such as layer removal [201] and hole drilling [118], but they are time-consuming and imprecise for polymer
substrates with microstructures. Non-destructive testing (NDT) methods are applicable for transparent plastic parts, such as birefringence [205, 206] and small-angle neutron scattering (SANS) [207], but these techniques need special instruments and the measurement resolution also may not be suitable for molded products with microstructures.

In this chapter, PMMA based microfluidic substrates were fabricated by micro injection molding, and direct thermal bonding was carried out on a custom-made bonding system. The integrity of microchannel profile after bonding was examined, and asymmetric deformation in transversally molded microchannels was observed. Based on this phenomenon, microchannel irregularity after direct thermal bonding was defined and utilized as the indicator to qualitatively evaluate the residual stress around microchannels in molded substrates. Design of experiment based on irregularity analysis was carried out to address which molding parameters are more significant in the development of molded-in residual stress, and subsequently to optimize the micro injection molding process with reduced residual stresses. Furthermore, the presence of stresses inside the molded substrates was demonstrated through photoelastic stress analysis in terms of phase retardation using a phase shift polariscope.
5.2 Experimental

5.2.1 Substrates preparation

The microfluidic pattern #3 was used in this chapter. PMMA plain substrates with microchannels and blank platform substrates (used as cover plates), as shown in Figure 5-1, were injection-molded using the Battenfeld HM25/60 injection molding machine. After molding, the replicated substrates were cut into three pieces of 25 mm × 25 mm each. The middle portion with micromixer pattern was then bonded to a blank cover plate by direct thermal bonding.

Figure 5-1  Schematic diagram of injection-molded substrates: (a) patterned plain substrate (pattern #3) and blank platform substrate (used as cover plate). Dashed-line squares indicate the cutting positions.

5.2.2 Thermal bonding

A custom-made thermal bonding system (see Figure 5-2) was developed in our laboratory. The molded micromixer substrate was brought into aligned contact with a mating homogeneous PMMA blank plate. Each chip assembly was then bonded by the thermal bonding system. In all the sealing experiments, bonding was performed at 85°C at a pressure of 0.8 MPa for 5 min. 85°C was used as the
bonding temperature because it is close to the nominal heat deflection temperature (HDT) of 90 °C supplied by material manufacturer, while the nominal $T_g$ is 100 °C. It is known that low bonding pressure can protect the microchannel from serious deformation, but in the present study, a higher pressure was used in order to produce microchannel with obvious deformation.

![Schematic diagram of custom-made thermal bonding apparatus.](image)

**Figure 5-2** Schematic diagram of custom-made thermal bonding apparatus.

### 5.2.3 Deformation measurement

After thermal bonding, care was taken to separate the substrates with a razor blade from the bonding edge of the chip. The detached substrate was adhered on a grinded aluminium plate in order to minimize the influence of possible warpage caused by separation. The topographies of the microchannels were measured using a confocal profilometer. Topographies of microchannels were also observed under a scanning electron microscope.
5.2.4 Residual stress evaluation

In order to demonstrate the molded-in residual stress status, a modified Senarmont phase shift polariscope [199] was used to get a full-field measurement of phase retardation. In this system, a monochrome green light source was used to illuminate the sample. After passing through the linear polarizer and quarter wave plate, the light is circularly polarized and projected onto the molded PMMA substrate. According to the stress-optical law, when the polarized light passes through the stressed material, phase retardation is produced and proportional to the principal stress difference, which in this case is derived from the molded-in residual stress. Upon going through the rotating analyzer, the light intensity is then captured by a CCD camera at analyzing orientations of 0°, 45°, 90° and 135° respectively. In this study, four phase shift images for each testing sample were captured by camera and processed by MATLAB program (see Appendix A1) to determine the principal-stress direction and the phase retardation [200]. Then the stress status in the molded substrates can be analyzed in terms of phase retardation.
5.3 Results and discussion

5.3.1 Microchannel deformation irregularity

In previous chapters and our previous work, microchannels can be replicated in PMMA substrate (see Figure 5-3(a)) with good fidelity by micro injection molding with optimal processing parameters. The processing conditions are: melt temperature (260 °C), mold temperature (75 °C), injection volume flow (32 ccm/s), injection pressure (1000 bar), holding pressure (580 bar), holding time (8 s) and cooling time (35 s). SEM micrographs present the morphologies of the inverted microchannel on BMG micromold (see Figure 5-3(b)) and the fabricated PMMA substrate with microchannel of 54.3 μm wide and 40.9 μm deep (see Figure 5-3(c)). In a typical direct thermal bonding process, the enclosed microchannel is expected to be symmetrically deformed. The schematic diagrams of origin microchannel and typically deformed microchannel are demonstrated in Figure 5-3(e-f). The arrows around the microchannel profile indicate the deformation tendency on each sidewall. This symmetric microchannel deformation has also been found as a regular phenomenon in other experiments on embossed thermoplastic substrates [139, 208, 209]. In our work, an irregular and asymmetric deformation phenomenon on the injection-molded microchannel was observed after direct thermal bonding process, as shown in Figure 5-3(d) and Figure 5-3(g). It was also observed but overlooked in a vacuum-assisted thermal bonding of PMMA microfluidic platform fabricated by injection molding [210]. It is probably because of the heterogeneity in bonding pressure distribution and the residual stress distributed around the microchannel [141]. In our bonding
experiments, a 1.2 mm neoprene gasket was placed between upper mold and upper substrate to equalize the pressure during bonding; besides, the investigated microchannels for comparison in the following experiment were carefully selected to further avoid the issue induced by pressure variation, which will be described in the next section. Compared to those embossed substrates in other works, injection-molded substrates are usually fabricated with larger internal stress. It should be noted that in micro hot embossing, the polymer flow path is very short depending on the microstructure dimension, and the processing temperature cycle is narrow with embossing temperature slightly above the glass transition temperature \( T_g \). By contrary, in micro injection molding, the melt flow path from nozzle to the far-end mold cavity is rather long, the flow speed is high, and the temperature non-uniformly drops from melting temperature to lower than \( T_g \) in mold cavities. Subsequently, both flow-induced and thermally-induced residual stresses can be developed in injection molding during filling and cooling stages.
Figure 5-3  (a) Photo of a replicated micromixer substrate, SEM micrographs of (b) inverted microchannel on BMG micromold, (c) replicated PMMA microchannel before thermal bonding and (d) after bonding, and schematic diagrams of microchannel deformation (e) before thermal bonding, (f) after thermal bonding with regular symmetric deformation and (g) with irregular asymmetric deformation. Arrows indicate the deformation tendency.


5.3.2 Effect of injection direction

In order to study the effect of melt injection direction on the occurrence of this asymmetric microchannel deformation, substrates with horizontal and transverse microchannel alignments were fabricated. In the molding experiment, the embossed micromixer BMG micromold was installed in the injection mold in two different orientations as indicated in Figure 5-4(a). Subsequently, two types of substrates with 0° microchannel alignment and 90° microchannel alignment with respect to injection direction were molded. The same molding parameters were used as described in the above section. After cutting, the middle part with microchannels was directly bonded to a blank substrate on the thermal bonding system. After bonding, the substrates were carefully separated and the profile of the microchannel at position Z was determined. The schematic diagram of measurement positions are shown in Figure 5-4(b). Measurement position Z was chosen because firstly it is located at the intersection of 0° and 90° alignment microchannel and secondly the distance from this position to the injection gate is identical.

The topographies of the microchannels along (0° alignment) and across (90° alignment) the injection direction are shown in Figure 5-5. After micro injection molding under the same processing condition, both 0° alignment and 90° alignment microchannels were well replicated with negligible variance (see Figure 5-5(b)). However, after thermal bonding, significant profile disparity between them was observed as shown in Figure 5-5(c-d). For 0° alignment microchannel, the symmetric deformation was within expectation, though there
were obvious top width widening and depth reduction (~7 μm shallower out of 40.9 μm). However, in contrast with 0° alignment microchannel, the microchannel aligning across the injection flow direction (90° alignment) was exceptionally deformed with the same processing conditions. For 90° alignment microchannel, the top width became wider and the depth lost more as shown in the profile of Figure 5-5(d). Furthermore, the cross-sectional profile was found to be asymmetric due to more dimension loss along the left sidewall, which is the farther side down the molten polymer injection direction.

![Figure 5-4](image)

**Figure 5-4**  Schematic diagrams of (a) the injection-molded substrate with indicated gate position and injection flow direction, and two differently oriented molds with 0° aligning (along injection direction) microchannels and 90° aligning (across injection direction) microchannels, and (b) measurement position Z at molded substrates of 0° and 90° alignments.
Figure 5-5  Topographic comparison between 0° alignment microchannel and 90° alignment microchannel measured by confocal profilometer (a-b) after micro injection molding and (c-d) after thermal bonding. Arrows indicate the injection flow direction.

The irregular microchannel deformation could be attributed to the molded-in residual stress, or probably the flow-induced residual stress caused by frozen-in large molecular orientations, even if it is only one order of magnitude smaller than the thermally-induced residual stress in absolute value [201]. When the temperature decreases towards the glass transition, the orientation relaxation time of polymer chain segments would increase more than exponentially [204]. If the solidification occurs before the polymer chains are fully relaxed to their state
of equilibrium, molecular orientation could be easily frozen in the glassy state. These polymer orientations can cause anisotropic optical behaviour [116] as well as anisotropic mechanical behaviour in directions perpendicular and parallel to the molten flow direction. Furthermore, for 90° alignment microchannel, the polymer molecular chains were injected and aligned across the microchannel and more resistance ahead of protrusive microstructures was faced during melt filling. Therefore, despite the fact that the 90° alignment microchannels can be replicated as well as the 0° alignment microchannels with proper molding parameters (see Figure 5-3(c) and Figure 5-5(b)), more internal stress can be developed around the microchannels aligning across the injection direction. During thermal bonding, when the molded substrate is subjected to varying temperature and large external force, the viscoelastic effects in response to environmental condition (e.g. stress relaxation) will dominate the dimensional stability [119].

All the above comparative results indicate that micro injection direction is profound on the deformation regularity of microchannels during the subsequent bonding process. Thus, it should be considered as a very crucial factor in microfluidic pattern design and replication of substrates by micro injection molding. But in fact, it is not always possible to design a microfluidic pattern with all microchannels aligning along the injection direction due to the existence of turning or zigzag channels, so it is important to figure out the dominant molding parameters in the irregular deformation issue in order to maintain as uniform microstructure dimension changes on the substrate as possible.
5.3.3 Effects of molding parameters

To further study the impact of molded-in residual stress on microchannel deformation during direct thermal bonding as well to re-optimize micro injection molding process with reduced residual stress, the irregularity of deformed microchannel after thermal bonding was defined in this study and considered as an objective function of several injection molding parameters.

According to literatures, melt temperature (A), mold temperature (B), holding time (C) and holding pressure (D) had profound effects on residual stress in molded plastic parts [120, 205, 207, 211] as shown in Table 5-1; therefore, these four parameters were taken into account in a design of experiment (DOE). Taguchi method was applied and three levels were considered for each factor (see Table 5-2). The selected level values were determined based on our previous experiences in avoiding regular molding defects such as short shot, flash, jetting, sink mark and warpage. All the interactions of any two independent factors were considered negligible in this design. Other molding parameters were kept constant through the DOE (i.e. injection pressure 1000 bar, injection volume flow 32 ccm/s, and cooling time 35 s). The Taguchi L9 orthogonal array (OA) experiment was designed as shown in Table 5-3 with 9 runs in total.
Table 5-1  Comparison of factors considered in DOE between previous research works and present study.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Factors considered *</th>
<th>Material</th>
<th>Evaluation method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Healy, 2006 [207]</td>
<td>Mold T</td>
<td>PS</td>
<td>Neutron scattering</td>
</tr>
<tr>
<td>Atlan, 2010 [120]</td>
<td>Melt T, Mold T, Cooling t</td>
<td>PS, HDPE</td>
<td>Layer removal</td>
</tr>
<tr>
<td>Present study</td>
<td>Melt T, Mold T, Holding P, Holding t</td>
<td>PMMA</td>
<td>Thermal bonding</td>
</tr>
</tbody>
</table>

* Underlined terms are significant factors concluded in corresponding articles. Notation definitions: T – temperature, P – pressure, v – volume flow and t – time.

Table 5-2  Micro injection molding parameters and selected levels in Taguchi method.

<table>
<thead>
<tr>
<th>Processing parameters (Factors)</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L1</td>
</tr>
<tr>
<td>A Melt temperature (°C)</td>
<td>250</td>
</tr>
<tr>
<td>B Mold temperature (°C)</td>
<td>75</td>
</tr>
<tr>
<td>C Holding time (s)</td>
<td>4</td>
</tr>
<tr>
<td>D Holding pressure (bar)</td>
<td>480</td>
</tr>
</tbody>
</table>
Table 5-3  Experimental runs of Taguchi L9 orthogonal array (OA).

<table>
<thead>
<tr>
<th>Design run</th>
<th>Factual run</th>
<th>Factors</th>
<th>S/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>#5</td>
<td>L1</td>
<td>L1</td>
</tr>
<tr>
<td>2</td>
<td>#8</td>
<td>L1</td>
<td>L2</td>
</tr>
<tr>
<td>3</td>
<td>#2</td>
<td>L1</td>
<td>L3</td>
</tr>
<tr>
<td>4</td>
<td>#7</td>
<td>L2</td>
<td>L1</td>
</tr>
<tr>
<td>5</td>
<td>#1</td>
<td>L2</td>
<td>L2</td>
</tr>
<tr>
<td>6</td>
<td>#9</td>
<td>L2</td>
<td>L3</td>
</tr>
<tr>
<td>7</td>
<td>#3</td>
<td>L3</td>
<td>L1</td>
</tr>
<tr>
<td>8</td>
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<td>L3</td>
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</tr>
<tr>
<td>9</td>
<td>#6</td>
<td>L3</td>
<td>L3</td>
</tr>
</tbody>
</table>

For each experimental condition in the randomized order, ten replicas with 0° alignment microchannels and ten replicas with 90° alignment microchannels were molded, but only the last two substrates for each alignment were used in direct thermal bonding process. After carefully separating the bonded substrates, the profile of the microchannel at position Z was determined. As demonstrated in Figure 5-6, there are three hatched areas, I, II and III, which are enclosed by 0° and 90° alignment microchannel profiles in the X-Y coordinate system. If the profile of deformed 0° alignment microchannel was considered as the standard profile under the chosen processing condition, the irregularity can be expressed as the percentage of irregularly deformed area (the sum of area I, II and III) related to the area surrounded by 0° alignment microchannel profile and X coordinate axis.
Therefore, the assessment criteria was defined as “Smaller irregularity can be explained as less irregular deformation resulting from better micro injection molding condition as well as less residual stress”. In Taguchi method, the calculated irregularity in percentile was used as the output response, for which, the quantity characteristic of “smaller-the-better” was selected to calculate the signal-to-noise (S/N) ratio according to equation (4-1), where n=2 is the number of response reading and $y_i$ is the individual response reading (irregularity value) under certain processing conditions.

The calculated results of S/N for factorial runs are listed in Table 5-3 and the main effects plot for S/N ratios is represented in Figure 5-7. Results of the Taguchi design show that melt temperature (factor A) is the most significant parameter to decrease deformation irregularity of 90° alignment microchannel. When the melt temperature is elevated, lower viscosity of molten polymer can
facilitate the filling into cavities. Furthermore, the core material with higher temperature needs more time to cool down, meanwhile the surface regions can undergo more sufficient self-annealing in this duration [120] and polymer chain segments can get more time to be re-oriented. Therefore, the residual stress around microchannels can be reduced. Mold temperature (factor B) shows second degree importance on reducing irregularity and residual stress in the surface layers. The possible reason is that for higher mold temperature, the whole temperature range between the melt and the mold is decreased, and the cooling rate of molten polymer in the surface region can be slowed down. Thus the corresponding frozen-in chain orientation and thermally-induced residual stresses can be further moderated. Holding time (factor C) and holding pressure (factor D) show slightly favourable effect on the reduction of irregular deformation. It is reported that increased holding pressure can result in decrease of total micro-scale shrinkage in the direction parallel to molding direction [212]; however, residual stress introduced during holding stage mainly distributes in the core as the surface region vitrifies earlier. Therefore, the contribution of holding pressure and holding time is minor in the case of molding microchannels in surface layers. A higher holding pressure of 780 bar is also used with the aim to check its individual effect. However, hump-like piling up of material occurs on the microchannel shoulder during demolding, which can be explained by volumetric expansion resulting from high holding pressure [124]. Injection volume flow higher than 32 ccm/s was also used, but non-negligible flash and visible jetting were observed in the molded part. In the present study, molded
parts with flash and jetting defect were not taken into account, but the effect of injection volume flow could also be expected and discussed. Jetting, induced by high injection volume flow, always occurs in the form of turbulent melt flow which is spurted from the thin gate section into a thicker mold cavity without wetting the cavity walls. It can lead to ripples on surfaces with unwanted stresses and non-uniform density. Higher injection volume flow can result in higher filling rate, which may tend to freeze more orientation on the surface and less in the core [213]. The negative effect of injection volume flow, to some extent, has also been supported by other simulation results and experimental observations [205, 214].

![Main effect plots of S/N ratios for factors: (A) melt temperature, (B) mold temperature, (C) holding time and (D) holding pressure.](image)

Based on the results of Taguchi method, proper molding parameters were concluded as melt temperature 270 °C (A3), mold temperature 85 °C (B3), holding time 12 s (C3) and pressure 680 bar (D3). We subsequently carried out
the validation test. The replication fidelity of microchannels was checked, and the predicted result of microchannel deformation irregularity with concluded molding condition was verified. The measured profiles of 0° and 90° alignment microchannels before and after thermal bonding are plotted in Figure 5-8. There was no obvious incomplete filling or dimension variance before thermal bonding as shown in Figure 5-8(a). The irregularity calculated from the profiles in Figure 5-8(b) is 21.4%, which is only half of the largest value, 42.7% for run #5 (combination of A1B1C1D1) in Taguchi experiment. It is also noted that the calculated irregularity is close to but still a little larger than that of run #9 (combination of A2B3C1D2). One possible reason is that, the whole temperature range between the melt and the mold for the combination of A3B3 is 10 °C wider than that of A2B3, which can result in higher cooling rate and cause more molded-in stress. Furthermore, when 270 °C was used as the optimal melt temperature, the constant cooling time of 35 s probably was insufficient. So the cooling time (time elapsed in the mold between end of holding and ejection of part) was varied individually as well, whilst the other parameters were kept constant. Figure 5-9 shows that microchannel deformation irregularity decreases to 8.1% with increasing cooling time till 60 s, at which the polymeric molecular chains near surface region get more sufficient re-orientation when the core cools down to mold temperature, and an in-mold equilibrium state is reached. The remaining irregular deformation can be resulted from anisothermal filling of molten polymer into cavities and unbalanced cooling rate through the layer depth, which are found to be the limits of current techniques.
Figure 5-8  Validation test results of 0° alignment microchannel and 90° alignment microchannel measured by confocal profilometer (a) after injection molding and (b) after thermal bonding. Bonding conditions are: temperature 85 °C, pressure 0.8 MPa, and duration 5 min.
Figure 5-9  (a) Effect of cooling time on microchannel deformation irregularity, (b) improved 3D topography result and (c) profile result of 90° alignment microchannel with prolonged cooling time of 60 s.
With above proper molding condition, the irregularity of 90° alignment microchannel can be decreased, and the residual stress in the surface region around microchannels can be reduced to some extent. Though residual stress is known to be an intrinsic characteristic during injection molding, and the irregularity of deformed microchannel might not be thoroughly eliminated with current techniques, the methodology proposed in this study provides a feasible approach to reduce the impact of molded-in residual stress and to improve the uniformity of microchannel deformation on a chip level in thermal bonding.

**5.3.4 Photoelastic stress analysis**

In order to make the measurement results comparative between the substrates with 0° alignment microchannels and those with 90° alignment microchannels, all the samples were orientated with the micro injection direction intentionally aligned along the polarizing axis of the polarizer. The orientation of the first principal stress for these two alignment types was experimentally determined to be 29.8° (± 2.3°) and 30.3° (± 3.1°) respectively, which correlates fairly well with each other. Therefore, further comparison in terms of phase retardation can be conducted.

Figure 5-10 shows several typical phase retardation maps acquired in different configurations. After the microchannels were replicated in 0° and 90° alignment directions, the retardation was comparatively analyzed in the focused zones as shown in Figure 5-10(a). These retardation maps are left-right inverted compared to the real samples due to camera acquisition. As shown in Figure
the measured retardation is fairly uniform in the blank substrate with no microchannel molded in it. In the presence of microchannels, the retardation map presents magnitude variation following a microchannel-like pattern, which may indicate that the stresses are concentrated around the microchannels after molding. Moreover, the molded-in stresses differ with different microchannel alignments, and the retardation variation for 90° alignment is more contrasting compared to that of 0° alignment. For 90° alignment, this distinct variation of retardation results from the large disparity of mold-in stresses in the bulk and those around microchannels, which then attributes to the irregular microchannel deformation when the stresses are getting released during thermal bonding. However, it can be seen from Figure 5-10(c) that, with the improved processing condition the overall retardation in the bulk is decreased to a lower degree. Moreover, the retardation variation for 90° alignment reduces to a level that is almost the same to that of 0° alignment. This decrease in retardation variation could be due to the fact that the residual stress has been further moderated with favourable molding parameters, such as higher melt temperature, higher mold temperature and longer cooling time after holding. Due to the improved molding process, the deformation irregularity of 90° alignment microchannels after thermal bonding can be reduced to an acceptable extent as shown in Figure 5-9(c).
Figure 5-10  (a) Schematic diagram of the focused zones on molded substrates for phase retardation measurement (highlighted by blue dashed lines), (b) typical phase retardation maps of blank reference, 0° and 90° alignment substrates molded with initial unimproved molding condition, and (c) typical phase retardation maps of blank reference, 0° and 90° alignment substrates molded with improved molding condition. (Solid-line arrows show the directions of 0° and 90° alignments with respect to injection direction. Dashed-line arrows show the left-right inverted alignment directions on retardation map. Blue circles indicate the Z position in confocal microscope measurement. Red dashed-dot lines indicate the positions for data extraction for the second step analysis.)
In order to further comparatively analyze residual stress in terms of phase retardation, the sampled data were extracted from retardation maps along the red dashed lines as shown in Figure 5-10. The average retardation values of blank substrates were calculated to be 19.27° and 17.58° for initial and improved molding condition. Assuming that the retardation in blank substrate is the same to that in the bulk of microchannel substrate, the absolute retardation difference between the extracted data and the reference can be determined. The profiles of absolute retardation difference are plotted in Figure 5-11(a) and Figure 5-11(b). The statistic results shown in Figure 5-11(c) are determined from the profile peak values which correlate to the residual stress around microchannels. It is evident from Figure 5-11 that, with unimproved molding condition, the profile of absolute retardation difference around 90° alignment microchannels shows distinct peaks (6.35°) over those of 0° alignment microchannels (2.33°). It also suggests that, in spite of the very small retardation (about 6.35°), the residual stresses molded around 90° alignment microchannels can lead to the failure in form of irregular deformation after thermal bonding. Furthermore, it can be implied that, by improving molding condition, the molded-in residual stress has been moderated to some extent that there is slight difference in retardation between 0° and 90° alignments.
Figure 5-11 Absolute retardation difference between 0°/90° alignment and reference which are extracted from retardation maps of substrates molded with (a) initial and (b) improved molding condition, and (c) statistic results obtained from peaks.
5.4 Conclusion

This chapter presents the effect of molded-in residual stress on microchannel deformation in direct thermal bonding. The result shows that molten polymer injection direction has significant impact on deformed microchannel profile in thermal bonding. Due to the molded-in residual stress induced in the surface region, microchannels molded across the injection direction were found irregularly deformed compared to those symmetrically deformed microchannel aligned along the injection direction. Based on the results of Taguchi method, higher melt temperature and higher mold temperature have been found to be significant in reducing microchannel deformation irregularity. Moreover, cooling time after holding should be accordingly prolonged in order to reach an in-mold equilibrium state and further decrease irregularity. Through photoelastic stress analysis in terms of phase retardation, the presence of residual stresses molded around microchannels has been demonstrated. By improving molding condition, the absolute retardation difference can be moderated which correlates to the reduction in molded-in residual stresses and decrease in microchannel deformation irregularity. Although this study does not thoroughly eliminate the phenomenon of irregular and asymmetric microchannel deformation, this work, from experimental point of view, provides better understandings of the effect of molded-in residual stress on microchannel dimension change in thermal bonding and the effects of significant molding parameters on residual stress reduction.
Chapter 6  Low Temperature Bonding
by Oxygen Plasma Treatments
and PVA coating

6.1 Introduction

Thermoplastics have been recognized as suitable alternatives to Si and glass because they are relatively inexpensive and amenable to volume production processes (e.g. micro injection molding, micro hot embossing and micro thermoforming) [11, 14]. However, there are some drawbacks intrinsic to thermoplastics which include hydrophobicity and low surface energy. This characteristic restricts thermoplastic devices to certain applications.

Therefore, a variety of surface modification techniques have been employed to increase the hydrophilicity and the surface energy [25, 215]. Surface modification with plasma is fast, straightforward and homogeneous. It can tailor the surface chemistry and topography of the thermoplastic surface by oxygenation, degradation and etching [178, 216]. However, the hydrophilization is typically unstable, and either a partial or complete hydrophobic recovery is usually observed on the treated thermoplastics [182]. Compared to plasma treatment, UV/ozone irradiation can generate higher surface energy and a thin surface layer with lower T_g, making it possible to bond mating substrates at low temperature with high strength [184], but the hydrophilicity can also be largely
lost upon DI water and solvents [139]. Photografting can permanently functionalize the surface property to be either hydrophilic or hydrophobic [186]. The hydrophilization on the very inert thermoplastic COC by two-step photografting was found to significantly reduce the protein adsorption [187, 188]. Other one-step photografting techniques were also investigated to improve the bond strength of COC microfluidic devices [189, 190]. However, both polar monomer and photo-initiator should be carefully prepared to be exposed under long time ultraviolet illumination. Moreover, the harsh solvents (e.g. acetone) used in photografting are not applicable to many thermoplastics (e.g. PMMA and PC). In the literatures, many work on surface modification have partially aimed at either a reliable surface functionalization technique for a proof-of-concept application or a versatile bonding method for the fabrication of disposable microfluidics, leaving the combination of these two requirements as an afterthought. In order to realize the potential of microfluidic devices, we should consider its final function at the earlier design and fabrication stages [217].

In this chapter, we propose a reliable bonding method with surface modification aiming at those applications requiring high and stable hydrophilicity. The proposed bonding method comprises two stages of oxygen plasma treatments, one simple polyvinyl alcohol (PVA) coating by thermal immobilization, and one low temperature thermal bonding process. PVA is a water-soluble polymer, which has been frequently used in biomedical applications due to its good film-forming ability, good mechanical strength, high hydrophilicity, biocompatibility, good chemical resistance and non-toxicity [218,
PVA coating has recently been introduced to microfluidics for surface hydrophilization in electrophoresis chips made from silica capillaries [220], PDMS [221], PMMA [222] and COC [139]. However, in these experiments, the PVA coating was applied to the already enclosed channels by external pumping, rinsing and then thermal incubation. Furthermore, those works focused only on the effects of PVA on the improvement of application performance. In this chapter, we evaluate the utility of PVA coating and oxygen pre-/post-plasma treatments on both microchannel walls and substrate surfaces as a method for effective bonding at low temperature without microchannel deformation, meanwhile for surface functionalization of many hydrophilic applications. The proposed fabrication method was successfully demonstrated by an oil-in-water droplet generation experiment, which is also believed to be applicable to many potential applications, such as biological analyses with low biomolecular adsorption, and capillary electrophoresis (CE) separation with low electroosmotic flow (EOF), etc.

6.2 Experimental

6.2.1 Substrate preparation

The microfluidic pattern #4 was used in this chapter. PMMA substrates, as shown in Figure 6-1(a-b), were injection-molded under the predetermined molding conditions: pre-drying (80 °C, 4 hours), melt temperature (270 °C), mold temperature (85 °C), injection pressure (1000 bar), holding pressure (680 bar), holding time (12 s) and cooling time (60 s) [223]. After micro injection molding,
the molded parts were cut into 25 mm × 25 mm and 25 mm × 50 mm footprint sizes. The latter type was used in the lap shear test to evaluate the bond strength. The proposed bonding process was illustrated in Figure 6-1(c-d). Firstly, several surface treatments were performed on the PMMA substrates, including oxygen plasma pre-treatment, PVA coating and oxygen plasma post-treatment. Then low temperature thermal bonding was conducted on the custom-made thermal bonding system.

![Image of injection-molded PMMA substrates and schematic diagrams of bonding processes]

Figure 6-1 (a-b) Injection-molded PMMA substrates: (a) blank plain substrate and (b) patterned platform substrate (pattern #4); and (c-d) schematic diagrams of bonding processes: (c) surface treatments through PVA coating and oxygen plasma pre- and post-treatment, and (d) low temperature thermal bonding.

6.2.2 PVA coating formation

The chemical structures of PVA and PMMA are shown in Figure 6-2. PVA powder (average $M_w$ 31000–50000 g/mol, 87–89 % partially hydrolysed) was purchased from Sigma-Aldrich. A 2% w/v PVA aqueous solution was prepared
by dissolving PVA powder into deionized (DI) water with stirring and heating at 85 °C for 24 hours. The PMMA substrates were immersed in the PVA aqueous solution at room temperature (RT, ~22 °C) for 10 min, then removed from the solution and incubated in an oven at 75 °C for 10 min for thermal immobilization. The above procedure can be repeated for several cycles resulting in a multilayer PVA coating. After the final cycle of PVA coating, the substrates were put in a dry cabinet for 24 hours. The immobilization temperature chosen is 75 °C, which is much lower than the nominal heat deflection temperature (90 °C) and T_g of 100 °C measured by DSC at 20 °C /min, in order to avoid any undesirable microchannel deformation during the thermal incubation. In the literature [224], a similar immobilization procedure with baking at 60 °C for 20 min showed a reliable film coating on PMMA samples. In another reported work, the multilayer PVA could be dynamically and irreversibly coated onto PMMA substrates even without thermal immobilization [225].

Figure 6-2 Chemical structures of (a) the base material PMMA and (b) the coating material PVA.
6.2.3 Surface characterization

The thickness of coated PVA layer was measured using a confocal profilometer by measuring the boundary steps between coated portion and uncoated portion. The latter was previously covered with a Scotch tape before PVA coating. A JEOL scanning electron microscope was also used to characterize the coated layer thickness on the cross-sectioned PMMA substrates. Depending on the microfluidic application, the number of coating cycles was varied to determine the acceptable coating thickness in order to keep the microchannel dimension integrity to a great extent. The measurements were taken on samples with and without oxygen plasma pre-treatment, and at least four measurements were taken on each sample.

DI water (H₂O) and ethylene glycol (C₂H₆O₂) were used to measure the contact angles at room temperature. The results were averaged from 10 readings obtained on each sample. The measured contact angles were used to calculate the surface energy according to the Owens-Wendt-Rabel-Kaelble (OWRK) method [198].

The chemical compounds of the PMMA surface before and after treatments were determined using a Perkin-Elmer GX Fourier-transform infrared spectrometer (FTIR) by attenuated total reflection (ATR). A total of 32 accumulation scans were carried out for each spectrum.

The surface roughness measurements were performed using the confocal profilometer. The measured surface area in each sample was kept constant at 93
μm × 93 μm. The reported Ra value was averaged from at least five topographies captured on each sample.

The coating stability in terms of hydrophilicity (or hydrophobic recovery) was monitored by measuring the static contact angle multiple times over one month after various surface treatments under two different storage conditions, modified from the method used in the literature [182]. The first set of samples was stored in the dry cabinet conditions: RT and relative humidity of 25%. The second set of samples was stored by immersion in the DI water at RT. Before each contact angle measurement, the samples were removed from the DI water and put in the dry cabinet at RT for 24 hours.

Differential scanning calorimetry (DSC) was carried out on a Q200 DSC instrument (TA Instruments, USA) to determine the Tg of PMMA and PVA. PMMA pellets were pre-dried in an oven at 80 °C before the measurement. PVA films with desired weight of about 15 mg were prepared in an aluminium pan through several repetitions of the coating recipe described in the previous section. The heating rate of DSC measurement was 20 °C/min, and the second heating cycle was recorded. The inflection midpoint of the heat flow shift was determined as the Tg.
6.2.4 Bonding performance evaluation

Bond strength was evaluated by lap shear test on an Instron testing machine. After lap shear test, the topographies of microchannels on the detached substrate were measured using the confocal profilometer. The morphology of detached surfaces and the cross-sectioned microchannel after thermal bonding were characterized using the SEM.

6.2.5 Droplet generation setup

In the fabricated droplet generation chip, the oil droplets were formed in the aqueous phase at the cross junction by focusing the oil stream with aqueous streams coming from two sides. The oil used in the setup was M5904 mineral oil (Sigma Aldrich, Singapore), while the aqueous phase was the mixture of 80.4% w/w G7757 glycerol (Sigma Aldrich, Singapore), 19.1% w/w DI water and 0.5% w/w L4509 sodium dodecyl sulphate (SDS) (Sigma Aldrich, Singapore). Glycerol was added to the aqueous phase to increase the viscosity while SDS was added to prevent the coalescence of droplets. The liquids were driven from syringes, with controlled volumetric flow rate, using KDS200 syringe pumps (KD Scientific, USA). The videos of the droplet formation were captured using HiSpec-4 high speed camera (Fastec Imaging, USA).
6.3 Results and discussion

6.3.1 Surface characterization

6.3.1.1 Coating layers thickness

As to the application of microfluidic devices, the coating layer thickness is important as it can change the microchannel dimension and may affect the functional results. When the coating process was repeated, multi-layer assembly can be formed on the PMMA surface, due to the hydrophobic interactions between main chain groups (-CH$_2$-CH$_2$-) and the intermolecular hydrogen bonding of hydroxyl groups between the adsorbed PVA in the dry state and PVA chain in aqueous solution [226]. The thickness of coating layer can depend on the solution concentration and the hydrophilicity of the base material [227]. Figure 6-3 shows the measured PVA layer thickness through different coating cycles with and without oxygen plasma pre-treatment. It is apparent from the figure that the coating layer on the pristine PMMA surface was thicker with dramatic thickness variance. Due to the hydrophobic property of the pristine PMMA surface, the PVA coating was non-uniform across the whole surface. By contrast, the oxygen plasma treated surface had better wettability to the aqueous PVA solution, resulting in thinner and more uniform coating layer on the substrate. The micrographs in Figure 6-3 show the cross-sections of two thermally bonded chips, each with two-cycle PVA coatings. Without oxygen plasma treatment, the two-cycle coating layer (A) was about 3.2 μm, while the coating layer (B) with oxygen plasma pre-treatment was only about 1.2 μm. It also should be noted that the surface activation can improve the surface energy and enhance the adhesion.
between the base material and the coating layer, which usually can be achieved by UV/ozone or corona discharge. The adhesion reliability is very important, especially in the end applications, e.g. oil-in-water droplet generation in a microchannel with hydrophilic PVA coating, which will be presented in the latter section of this chapter.

Figure 6-3  PVA coating layer thickness with respect to varied cycles of coating on pristine and oxygen plasma pre-treated PMMA substrates. Inset SEM micrographs show the cross-sections of bonded PMMA substrates.

6.3.1.2 Contact angle and surface energy

The surface wettability and surface energy were examined by measuring the contact angles using DI water and ethylene glycol as the testing liquids with their known surface energy components [228] listed in Table 6-1. Figure 6-4 shows the average contact angles of these two testing liquids and the calculated surface energies on the PMMA substrate with different treatments. The hydrophobic
surface of the pristine PMMA had a static water contact angle of 75.0° ± 0.9°, agreeing quite well with the previous reported values of 75 ± 2° [229] and 76 ± 4° [133]. The oxygen plasma treatment can significantly reduce the water contact angle to 42.7° ± 2.2°. After PVA coating, the water contact angle decreased further to 20.0° ± 2.4° showing considerably increased surface hydrophilicity. This could be due to the hydrophilic nature of PVA, containing several polar functional groups. After the oxygen plasma post-treatment on the coated PVA layer, the water contact angle decreased further to 13.9° ± 1.7°. After each treatment, both the polar component and the total surface energy increased. As the polar component corresponds to the various polar groups (e.g. −OH, C=O, C−O, O−C=O, et al.) on the modified surface, the water contact angle decreased as the polar component of surface energy increased.

<table>
<thead>
<tr>
<th>Liquid</th>
<th>( \gamma_l^d ) (mJ/m²)</th>
<th>( \gamma_l^p ) (mJ/m²)</th>
<th>( \gamma_l ) (mJ/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DI water</td>
<td>21.8</td>
<td>51.0</td>
<td>72.8</td>
</tr>
<tr>
<td>Ethylene glycol</td>
<td>29.3</td>
<td>19.0</td>
<td>48.3</td>
</tr>
</tbody>
</table>
6.3.1.3 FTIR

ATR-FTIR measurements were carried out to study the differences in modified chemical structure of PMMA with different treatments. Figure 6-5(a) shows the ATR-FTIR spectra of PMMA before and after different surface treatments, while Figure 6-5(b) shows the subtracted spectra.

The spectral change after the oxygen plasma treatment was noticeable with two absorption peaks at 1722 cm\(^{-1}\) and 1140 cm\(^{-1}\) showing the presence of C=O and C−O groups, respectively. The increase in these oxygen-containing functional groups revealed the oxygen insertion into the polymer matrix during the plasma treatment. This finding correlates well with the earlier observations that, due to these functional groups the hydrophilicity and surface energy can be increased. This hydrophilic surface with higher surface energy can facilitate the
uniform coating as we observed in the thickness measurement. Moreover, the high surface energy can also promote the adhesion between the coating layer and the base substrate which will be discussed in the following section in terms of bond strength measured by lap shear test.

After PVA coating, the subtracted spectrum showed a broad noticeable absorption peak around 3100-3600 cm⁻¹ which could be due to the presence of hydroxyl group (−OH) of PVA molecules. The absorption peaks corresponding to −CH stretching vibrations, CH₂, CH₃ and vibration of CH₂ bond were also observed. The bands corresponding to carbonyl functional groups were due to the residual acetate groups remaining after the hydrolysis of polyvinyl acetate (PVAc). All the above observed peaks in the spectrum clearly revealed the major groups associated with PVA chemical structures, indicating the successful attachment of PVA onto the PMMA substrate.

In the subtracted spectrum between PVA coating and oxygen plasma post-treatment, there was only slight increase in −OH and C−O associating with the insignificant change in both water contact angle and surface energy. In general, there was no noticeable change in the spectrum, indicating that the main chemical composition and chain interaction of PVA was unchanged after oxygen plasma post-treatment.
Figure 6.5  (a) ATR-FTIR spectra and (b) the spectral differences: O—pristine, OP—pristine and OPO—OP, where ‘O’ represents oxygen plasma pre- or post-treatment, and ‘P’ represents PVA coating.
6.3.1.4 Surface roughness

It is known that the increase in surface energy especially the polar components can either be attributed to the increased polar groups, or originate with the increased surface roughness [184]. The comparative surface roughness values and typical observations on samples with different treatments are shown in Figure 6-6. After micro injection molding, the roughness on the pristine PMMA was about 10 nm, which then increased to 14 nm after oxygen plasma treatment. The change in surface roughness can be resulted from etching or degradation of PMMA during plasma treatment [184]. After PVA coating the surface became smoother with a roughness value of about 7 nm, which indicated that the effect of surface roughness on surface energy was negligible compared to the effect of the increased polar groups as analyzed in the previous section. It is evident from Figure 6-6 that the oxygen plasma post-treated surface exhibited a higher surface roughness of 11 nm, which can also be attributed to etching or oxygenation in the oxygen plasma process [230]. The higher surface roughness probably can contribute to the improved wettability and surface energy, which might not be solely explained by ATR-FTIR observations.
Figure 6-6  (a) Calculated surface roughness values and (b) typical surface morphologies of the pristine and treated surfaces (treatments in an accumulative sequence).


6.3.2 Bonding performance

6.3.2.1 Bond strength

The bond strength of PMMA substrates with different treatments were measured and compared, as shown in Table 6-2. For the untreated PMMA substrates, the bond strength of 0.34 MPa can be obtained at 85 °C, which is in the vicinity of the glass transition range. When thermal bonding was immediately conducted after oxygen plasma pre-treatment, the bond strength at 85 °C can be improved to 0.45 MPa. This increment in bond strength can be attributed to the increase in the surface energy especially the polar component and the surface roughness, which are resulted from the oxygen plasma pre-treatment. During thermal bonding process, the increased surface energy can facilitate the interaction between the treated surfaces and enhance the intimate contact [184].

When a PVA layer was coated onto the PMMA substrates without oxygen plasma pre-treatment, the obtained bond strength was weak at 0.13 MPa. From the SEM micrograph shown in Figure 6-7(a), the coated PVA layer was easily detached from the PMMA surface after strength test. This result indicated that de-bonding mainly occurred at the coating interface, due to the inferior adhesion between the coated PVA and the PMMA. Without surface activation, PVA can only be attracted to the PMMA surface by hydrogen bonding [225], because the surface charge can arise from enhanced autolysis of water at hydrophobic surfaces with the preferential adsorption of a hydroxide ion [231]. With oxygen plasma pre-treatment, the attachment of PVA layer onto the PMMA surface can
be enhanced due to the increased surface energy, as analyzed in the previous section. Besides, when PMMA was oxidized by oxygen plasma, more hydrogen-bond donors can be supplied at the PMMA surfaces for the spontaneous adsorption of the coating polymer. The enhancement in adhesion between PVA and PMMA can be interpreted from Figure 6-7(b). The coated PVA layer still adhered firmly onto the PMMA surface, while the zig-zag failure observed on PVA was due to the shear force during test.

During thermal bonding, the PVA films coated on the mating PMMA surfaces served to bond to each other, and the $T_g$ should be taken into account because it correlates with the molecular segmental mobility and determines the processing window of temperature. The DSC curves of PMMA and prepared PVA film are presented in Figure 6-8. The $T_g$ of pristine PMMA and PVA was measured to be 100 °C and 71 °C, respectively. The measured $T_g$ of PVA was smaller than the value 85 °C reported in the literature [227], but agreed well with other reported results between 59 °C and 74 °C [232]. When the applied bonding temperature (70 °C) was around the $T_g$ of PVA, the molecular chains can actively move and interdiffuse to each other at the mating interface, and the obtained bond strength was 0.18 MPa. When the temperature was elevated to 85 °C, the bond strength can be improved to 0.26 MPa; however the microchannel was distorted at the same time.

It was interesting to note that when the coated PVA were then treated again with the oxygen plasma, the obtained bond strength was noticeably improved to about 0.32 MPa at 70 °C, which was close to the strength obtained at
85 °C for untreated PMMA. The possible reason for this substantial improvement in bond strength could be that, the post-treatment of oxygen plasma served to improve the surface wettability and enabled easier intimate contact between the surfaces during thermal bonding. The roughened surface can also increase the surface contact area and enhance the molecular diffusion across the bonding interface. It was reported that due to the complexity involved in the oxygen plasma process (simultaneous etching and oxygenation), some amorphous and crystalline fractions can be removed by plasma and the T_g of PVA film decreases [230].

Table 6-2  Bond strength of thermally bonded PMMA with different treatments (bonding pressure 1 MPa and boning time 15 min).

<table>
<thead>
<tr>
<th>Treatment on PMMA</th>
<th>Temperature (°C)</th>
<th>Bond strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untreated</td>
<td>70</td>
<td>Nil</td>
</tr>
<tr>
<td></td>
<td>85</td>
<td>0.34</td>
</tr>
<tr>
<td>O_2 plasma</td>
<td>70</td>
<td>Nil</td>
</tr>
<tr>
<td></td>
<td>85</td>
<td>0.45</td>
</tr>
<tr>
<td>PVA without O_2 plasma</td>
<td>70</td>
<td>0.13</td>
</tr>
<tr>
<td>O_2 plasma + PVA</td>
<td>70</td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td>85</td>
<td>0.26</td>
</tr>
<tr>
<td>O_2 plasma + PVA + O_2 plasma</td>
<td>70</td>
<td>0.32</td>
</tr>
</tbody>
</table>
Figure 6-7  SEM micrographs of failure surfaces after lap shear tests (a) without and (b) with oxygen plasma pre-treatment.

Figure 6-8  DSC curves showing the measured $T_g$ of PMMA and PVA, respectively.
6.3.2.2 Microchannel integrity

For the microchannel dimensional integrity analysis, the PMMA substrates with microchannel design dimension of 200 $\mu$m × 200 $\mu$m were injection-molded and bonded with PVA coating and oxygen plasma pre- and post-treatment. The thermal bonding experiments were conducted at temperature of 70 °C with bonding pressure of 1 MPa and bonding time of 15 min. The morphology and dimension of microchannel were examined using an SEM and a confocal profilometer. The SEM micrographs shown in Figure 6-9(a-d) present the microchannels on the embossed BMG micromold, the injection-molded pristine PMMA substrate, the PVA-coated PMMA substrate with oxygen plasma pre-treatment, and the manually detached PMMA substrate after thermal bonding, respectively. It is apparent from Figure 6-9(c) that, all the surfaces became smoother after PVA coating, indicating the successful attachment of PVA on both the substrate surface and the microchannel sidewalls. After thermal bonding, the manually detached substrate presented the fracture of PVA layer as shown in Figure 6-9(d). The microchannel profiles on the samples used in the SEM observation were measured as shown in Figure 6-9(e-g) for comparison. The microchannels were replicated from the BMG micromold to the PMMA substrate with high fidelity by micro injection molding, and the dimension was negligibly affected by the coated thin PVA layer. It is also evident that the microchannel integrity was well retained without distortion after low temperature thermal bonding. A thermally-bonded droplet generation chip is shown in Figure 6-9(h) and the cross-sectioned microchannel is shown in Figure 6-9(i). It can be seen
from the SEM micrograph that after thermal bonding, the microchannel walls remained vertical and no obvious microchannel collapse was observed. All the above observations could be attributed to the fact that the bonding process was conducted at the temperature much lower than the heat deflection temperature (90 °C) and the $T_g$ (100 °C) of the bulk PMMA.

Figure 6-9  (a-d) SEM micrographs of microchannels on (a) BMG micromold, (b) injection-molded pristine PMMA substrate, (c) PVA-coated PMMA substrate, and (d) manually detached PMMA substrate after thermal bonding; (e-g) Profile comparison of the microchannel measured on the samples used in the SEM observation; (h) Photo of a thermally-bonded droplet generation chip with (i) SEM micrograph of the cross-sectioned microchannel.
6.3.3 Hydrophilicity stability

Figure 6-10(a) and Figure 6-10(b) show the hydrophilicity stability test results of treated PMMA samples exposed to air and DI water, respectively. The contact angle of 75.0° on the pristine PMMA surface is included for reference.

![Figure 6-10](image)

Figure 6-10 Static water contact angles of hydrophilicity stability tests measured on the surface-treated PMMA substrates under (a) dry and (b) wet storage conditions.
The oxygen plasma treated PMMA surfaces present evident hydrophobic recovery from 42.7° (± 2.2°) to 56.2° (± 1.6°) and 56.1° (± 2.7°) after one month for the samples exposed to air and DI water, respectively. This recovery can still extend till the contact angle reaches to near the original level of pure PMMA [181, 182]. The results showed that, either in dry or in wet storage environment, PMMA with oxygen plasma treatment has very instable hydrophilicity over a period of time. Hydrophobic recovery of the surface can also cause the inconsistency in the wetting properties of microfluidic chips during the end applications.

The aging results of the PVA coated samples exposed to the air showed that the surface hydrophilicity can remain stable with the contact angle around 20° for over one month. The stability correlated fairly well with the reported results in the literature [224]. After the oxygen plasma post-treatment, the modified surface underwent a quick hydrophobic recovery in the air from 13.9° (± 1.7°) to 16.5° (± 1.9°) after one day as shown in the inset figure, and its wettability stabilized with the contact angle still lower than that of the surface without plasma post-treatment. This observation suggested that the oxygen plasma post-treatment can permanently modify the PVA surface chemistry and morphology resulting in a more hydrophilic surface.

After the PVA coated samples were immersed in DI water, the measured contact angle increased from 20.0° (± 2.4°) to 30.9° (± 1.6°) within 5 days and then stabilized for the rest testing days. The similar trend in contact angle variation was also observed for the coated samples with oxygen plasma post-treatment,
which increased from 13.9° (± 1.7°) and stabilized at about 22.8° (± 1.7°) after 5 days. Due to the plasma post-treatment, the hydrophilicity could be retained at a higher level with the contact angle close to that of PVA exposed to the air. It also should be noted that PVA is a water-soluble synthetic polymer. If the coated PVA layer was dissolved in the DI water, the surface wettability would be dominated by the exposed base PMMA. However there was no full hydrophobicity recovery observed on the DI water immersed samples. It has been reported that the solubility of PVA in water depends on its degree of hydrolysis, and the PVA grade with high degree (87–89% in this case) of hydrolysis has low solubility in water [233]. The presence of large amount of hydroxyl groups in highly hydrolysed PVA can enhance the intra- and inter-molecular hydrogen bonding of adjacent hydroxyl groups and subsequently can greatly reduce the water solubility. The water temperature must be raised to above 70 C° to accelerate the dissolution of PVA [227], which was highly evident in the aqueous solution preparation. In this study, the increase in contact angle could be attributed to the initial dissolution of PVA into the water due to the residual hydrophobic acetate groups. After reaching the equilibrium state, the hydrophilicity can then stabilize for very long time.

All the above results suggested that the PVA coated PMMA substrate with oxygen plasma post-treatment presented the lowest contact angle and the most stable hydrophilicity, either in dry or wet storage conditions. Therefore, the microfluidic chips fabricated with the proposed modification and bonding
method can be stored with highly stable hydrophilicity and used for long shelf-life hydrophilic applications.

6.3.4 Oil-in-water (O/W) droplet generation

With the proposed fabrication method, several droplet generation chips were fabricated and stored under DI water condition. After one week of immersion in the DI water, they were tested for the oil-in-water droplet generation. Figure 6-11 shows the generated droplet volumes at different flow rate ratios between the continuous aqueous phase ($Q_c$) and the dispersed oil phase ($Q_d$). Each data point in the graph of the figure was collected from video capturing of over 100 generated droplets, and analysed by a self-written software using OpenCV image processing library. As expected, within the same flow rate ratio, the droplet volume decreased as the continuous phase flow rate increased. This was due to the increment of viscous stress from the continuous phase streams that made the dispersed stream to break up faster. The insets in the figure show the micrographs of the freshly formed oil droplets at flow rate ratio of 5, with different continuous phase flow rate: 500, 1000, 1500, and 2000 μL/h, respectively. The results from this experiment showed the bonded device was capable of generating monodispersed oil droplets with controllable sizes and frequencies using different sets of flow rates.
Figure 6-11 Effect of continuous aqueous flow rate on droplet volume at different flow rate ratios, $Q_c/Q_d = 2.5$, 5, and 10; Inset micrographs show the monodispersed oil droplets in aqueous solution at flow rate ratio of 5 with different continuous phase flow rates of 500, 1000, 1500, and 2000 $\mu$L/h, respectively.

The adhesion stability of PVA coating onto PMMA surface can also be evaluated from the delamination of PVA layer during microfluidic applications. Control chips were fabricated by thermal bonding of pristine PMMA substrates at 85 °C under 1 MPa without oxygen plasma pre-treatment. The procedure of dynamic coating PVA in the microchannel was adopted from the literatures [139, 222]. The 2% w/v PVA solution was injected into the sealed microchannels using a syringe at RT for 10 min. Then the microchannels were emptied by pumping air through the chip for 5 min. Upon drying, the chip was incubated in an oven at 70 °C for 10 min. The filling/evacuation/incubation process was repeated for two times for a better coating. Figure 6-12 shows the downstream microchannel on
the droplet generation chip. It can be found in Figure 6-12(a) that it was quite easy for the coated PVA layer to delaminate from the microchannel sidewalls during the experimental operation. The delaminated PVA layer was washed away by the aqueous solution and accumulated at the downstream microchannel. In contrary as shown in Figure 6-12(b), no delamination of PVA was observed, indicating that the oxygen plasma treatment can improve the coating adhesion and the uniformity, ensuring a hydrophilicity-reliable and stable coating during the application. Moreover, due to the low temperature bonding method, the clarity and surface finish of PMMA substrates can be highly preserved after bonding, as comparatively shown in Figure 6-12.

![Figure 6-12](image)

Figure 6-12 Photos of the downstream microchannel during oil-in-water droplets generation showing (a) the delaminated PVA layer and (b) the improved adhesion without PVA delamination by oxygen plasma pre-treatment.
6.4 Conclusion

The low wettability and low surface energy of thermoplastics can affect the ease of bond strength development during thermal bonding and limit the use of thermoplastic microfluidic devices for many applications. In this study, a novel bonding method via PVA coating and oxygen pre- and post-treatments, followed by a low temperature thermal bonding process, was proposed as an alternative fabrication method for obtaining sealed PMMA microchannels with high dimensional integrity and highly stable hydrophilicity.

The oxygen plasma pre-treatment was found to be effective in improving the coating layer uniformity and enhancing the adhesion between the coated PVA layer and the PMMA surface due to the increased polar groups and the roughened surface. Due to the high surface energy and low \( T_g \), the coated PVA layer can serve as a medium material to bond the mating substrates at the temperature lower than the glass transition range of the substrate material. Therefore, the undesirable microchannel distortion coming along with the conventional thermal bonding method can be avoided. The oxygen plasma post-treatment was found to be effective in increasing surface energy of the coated PVA by roughening its surface. At the bonding temperature close to \( T_g \) of the PVA layer, the bond strength developed with oxygen plasma post-treatment can be improved and was comparable to that obtained on pristine PMMA by pure thermal bonding at a temperature near the \( T_g \) of PMMA. Moreover, the oxygen plasma post-treatment can further render the surface to be more hydrophilic and more stable in either dry or wet storage environments. The monodispersed oil-in-
water (O/W) droplets were successfully and reliably generated in the hydrophilic microfluidic device fabricated with the proposed bonding method.
Chapter 7  Bonding with Strength Enhancement by Ultrasonic Actuation

7.1 Introduction

Rigid thermoplastics, e.g. Polymethyl methacrylate (PMMA) and Polycarbonate (PC), are preferred materials for fabricating less deformable features [19], but their applications are limited due to their low chemical resistance [234]. As a promising thermoplastic, cyclic olefin copolymer (COC) becomes an attractive alternative, due to its high chemical resistance, high biological inertness, low moisture absorption, long-term surface treatment stability and good transparency in visible and near ultraviolet spectrum [235]. Moreover, various grades are commercially available and they are quite suitable for volume replication technologies [236], e.g. micro hot embossing (μHE) and micro injection molding (μIM).

Bonding aims to seal open microchannels in microfluidic devices, which however, has been a bottleneck in the fabrication of polymeric microfluidic devices [25]. Existing bonding methods for thermoplastic microfluidic devices include thermal bonding [51, 155, 237], adhesive bonding [238-240], solvent bonding [132, 140, 141], UV grafting [186, 190], plasma treatment [133, 216, 241], UV/UV−O₃ treatment [139, 183, 202], microwave bonding [242-244] and ultrasonic welding [159, 161, 165]. There are several considerations in selecting a
suitable bonding method, which include bond strength, integrity of microchannels, homogeneity of microchannel sidewalls, surface chemistry after bonding, and chemical compatibility on bond interfaces. Thermal bonding is one of the preferred methods because the method is straightforward, compatible to various polymers, and advantageous over adhesive bonding, solvent bonding, and grafting in keeping material homogeneity. In a typical thermal bonding process, substrates are heated to around the glass transition temperature (T_g) and compressed under pressure for a certain duration. The interfacial bond strength is developed due to surface wetting and interdiffusion of polymer chain segments across the bonding layers [145]. However, the high bond strength is always obtained with the big loss of microchannel integrity under high temperature over T_g, or vice versa. At temperature lower than T_g, the bond strength can also be slowly developed, and the rate depends on the bonding conditions, polymer chemical structure, molecular weight, polydispersity and surface wettability [145]. Therefore, surface modification, such as UV−O_3 treatment, has been applied prior to thermal bonding, in order to facilitate the bond strength development at a low temperature. But surface modification performs to the whole device and changes the microchannel wettability, which may not be acceptable in some applications.

In recent research [167-170], ultrasonic energy has been introduced in rapid bonding of flat thermoplastic microfluidic substrates at low temperature. In contrary to microwave bonding [242-244] and ultrasonic welding [159, 161, 165], there is no polymer melting involved in this promising bonding process [167]. It
was reported that the proposed thermal assisted ultrasonic bonding can ultrasonically bond PMMA substrates at temperature 20−30 °C lower than its $T_g$ in tens of seconds with good bond strength and minor microchannel deformation [170]. Moreover, it was applicable to bond multilayer PMMA microfluidic [169] and planar nanofluidic devices [168]. The bonding principle is believed to be thermal diffusion with the assistance of ultrasonic oscillating force acting on the substrates instead of static compression force. However, there are limited works to investigate the bonding failure mechanism, interfacial temperature measurement, strength development and microchannel profile distortion analysis; moreover, further efforts should be made to extend its applicability to other preferred thermoplastic, such as COC.

The focus of this chapter is to further investigate the application and effects of ultrasonic energy in microfluidic device bonding. A rapid bonding enhancement method is proposed with auxiliary ultrasonic actuation, which is advantageous over pure thermal bonding method. In our experiments, we found that it is almost impossible to directly ultrasonically bond COC substrates at low temperature without the occurrence of polymer melting due to the localized energy concentration. The reasonable bond can only be formed in the presence of a prior intimate contact between the bonding surfaces. With the assistance of auxiliary ultrasonic energy applied onto the preheated substrates in a few seconds, the bond strength can be enhanced and comparable to the strength obtained by pure thermal bonding above the $T_g$. Furthermore, the loss in microchannel integrity is found to be negligible.
7.2 Experimental

7.2.1 Substrate preparation

The microfluidic pattern #4 was used in this chapter. COC substrates, as shown in Figure 7-1, were fabricated with the size of 75 mm × 25 mm × 1.5 mm with the microfluidic pattern replicated in the middle portion. The molding conditions were predetermined as follows: pre-drying (60 °C, 4 hours), melt temperature (230 °C), mold temperature (55 °C), injection pressure (800 bar), holding pressure (350 bar), holding time (10 s) and cooling time (25 s). After injection molding, molded plates were cut into 25 mm × 25 mm and 25 mm × 50 mm footprint size. The latter type was used in the lap shear test to evaluate the bond strength. Before bonding, the substrates were cleaned in ultrasound bath with acetone and isopropyl alcohol (IPA) respectively for 5 min, flushed by DI water, and dried in oven at 60 °C for four hours.

Figure 7-1  Injection-molded COC substrates: (a) blank plain substrate (used as cover plate) and (b) patterned platform substrate (pattern #4).
7.2.2 Ultrasonic actuation

Ultrasonic actuation experiments were carried out on a benchtop ultrasonic bonding system as shown in Figure 7-2. Major ultrasonic apparatuses include a Rinco MP351 ultrasonic welder and a Rinco SDG35 ultrasound generator. The ultrasonic frequency is 35 kHz and the maximum operation power of the generator is 750 Watt. A homemade fixture and a thermal insulation pad were clamped on the leveling anvil. The fixture can be heated up to a desired temperature by a self-contained Watlow ceramic heater cartridge equipped with a Watlow EZ-Zone temperature controller. A homemade compressed-air cooling unit was installed in the transducer compartment to protect the converter from overheating.

Before ultrasonic actuation, thermal bonding was applied to achieve the intimate contact between a COC cover plate and a substrate on a home-made bonding system [223]. The assembly of a cover and a substrate was secured on the fixture, and a Type K thermocouple was attached on the substrate outer surface by a Nitoflon PTFE (Polytetrafluoroethylene) tape with excellent heat-resistance. Then the assembly was heated up to a desired temperature. Driven by compressed air, the horn was pushed down and pressed onto the assembly. Once the target pressure was reached, ultrasonic vibration was generated. The 35 kHz ultrasonic vibration with preset amplitude transmitted through the horn to the thermoplastic substrates. The ultrasonic vibration was applied in the direction perpendicular to the substrates. The bonding process was set under time mode, and the expected welding depth was set to zero. The vibration was terminated.
after pre-set time, while the horn was held onto the parts until it reaches a pre-determined holding time. Then the sample was unloaded for cooling down naturally. For bond strength comparison, thermal bonding without ultrasonic actuation was also carried out on the same home-made bonding system.

Figure 7-2 Ultrasonic bonding system used in the present work: (a) the complete system and (b) a schematic diagram of the close-up ultrasonic bonding apparatus.
Interfacial temperature monitoring during the process was done via a pre-embedded sheathed thermocouple by thermal compression. The nominal diameter of the element-line of the thermocouple was 80 μm, while the statistical diameter of the junction-tip was 197.8 (±11.2) μm. The measurement signal was collected by a Dewetron DAQ-Therm data acquisition device under a sampling rate of $1 \times 10^4$ s$^{-1}$ and recorded by a DeweSoft data logging software.

In order to reduce the effect of parallelism on bonding quality, the anvil was leveled with Fujifilm Prescale pressure measurement films. Alternatively, carbonic paper can also be used for coarse leveling adjustment.

### 7.2.3 Bonding performance evaluation

Bond strength was evaluated by lap shear test on an Instron testing machine. The profile and 3D topography of microchannels on substrates were measured using a confocal profilometer. After lap shear test, the morphology of debonded surfaces was characterized with a JEOL scanning electron microscope.

### 7.2.4 Thermal properties measurement

Since the grades can vary for commercial Topas COC, differential scanning calorimetry (DSC) and dynamic mechanical analysis (DMA) were carried out to determine its thermal properties under static and dynamic conditions respectively. The DSC experiments were conducted on a Q200 differential scanning calorimeter (TA Instruments, USA). Polymer pellets were pre-dried in oven at temperature 20 °C lower than nominal $T_g$ for 4 hours to remove moisture,
and cut into thinner sections in order to cover as much of the pan bottom as possible. The temperature of the furnace was equilibrated at 30 °C then ramped to 20 °C above the suspected glass transition region with a rate of 20 °C/min. The inflection midpoint of the heat flow shift was recorded as the glass transition temperature. The DMA experiments were carried out on a Q800 dynamic mechanical analyzer (TA Instruments, USA) using single cantilever method. Plate samples were injection-molded and cut into strips with rectangular footprint of around 25 mm x 10 mm x 1.5 mm. Single frequency test (1 Hz) and frequency sweep test (from 0.2 Hz to 20 Hz) were carried out with temperature ranging from 35 to 100 °C and isothermal steps of 5 min for every increment of 5 °C. Storage modulus (E'), loss modulus (E'') and Tan delta (Tan δ) were recorded. According to ASTM international standard designation E1640, the glass transition shall be taken as the extrapolated onset to the sigmoidal change in storage modulus observed in going from the rigid region to the rubbery region of the thermoplastic being tested by DMA.
7.3 Results and discussion

7.3.1 Failure analysis

Compared to vibration welding (180 – 240 Hz), ultrasonic welding (up to 40 kHz) of thermoplastics requires better surface preparation, as the surface impurities cannot be automatically removed by the depletion of the initial surface [245]. We found that the intimate contact preparation between the bonding surfaces of substrates was a crucial prerequisite prior to the introduction of ultrasonic energy. Figure 7-3 shows some typical defects observed on bonding interface after ultrasonic actuation with improper intimate contact. Without sufficient intimate contact, localized welding, as shown in Figure 7-3(a), is usually observed on the bonding interface after ultrasonic actuation, which probably can be attributed to surface asperities (e.g. surface unevenness and contamination particles). In the presence of ultrasonic actuation, these undesired asperities can act as the energy directors which are usually used in the conventional ultrasonic welding process [160]. These undesirable energy directors can localize the auxiliary ultrasonic energy and cause dramatic local thermal concentration. They rapidly melt, bond the two surfaces and prevent the further transmission of ultrasonic vibration onto the interface. Moreover, multi-scale voids, as shown in Figure 7-3(b-c) sometimes occurred concurrently with these localized welding due to trapped air or cavitation effect, which can reduce the bond strength and cause local leakage if they overlap the microchannels. In the case of microfluidic device bonding, the replication quality of microchannel is another important consideration. For an improperly molded substrate, the
undesired hump structure on the microchannel shoulder (see Figure 7-3(d)) caused by demolding during micro injection molding, can also lead to localized melting as shown in Figure 7-3(e). Furthermore, a fully intimate contact is highly recommended, because a partially intimate contact is prone to cause edge melting observed in the following ultrasonic actuation, as shown in Figure 7-3(f). The interfacial friction at edges can generate more heat and melt the edges earlier than other locations [246].

Therefore, the initial surface condition has significant impact on the bonding quality and yield when a subsequent ultrasonic vibration is applied on the substrates. In order to eliminate the surface asperities, pre-bonding by thermal compression was applied to achieve an initial surface wetting on the bonding interface. Through visual inspection of any absence of intimate contact, the proper thermal bonding parameters were found to be 0.32 MPa, 5 min and 75 °C, with which a void-free intimate contact was achievable.
Figure 7-3  Typical defects observed on bonding interface after ultrasonic actuation without prior intimate interfacial contact: (a) SEM micrograph of localized spot melting, (b-c) optical micrographs of voids in localized melting area, (d) profile of hump structure on the microchannel shoulder due to improper replication, (e) SEM micrograph of localized melting due to hump defect, and (f) SEM micrograph of edge melting due to partially intimate interfacial contact.
7.3.2 Interfacial temperature analysis

As the bond strength develops at the interface, it is very important to monitor the interfacial thermal history. A typical thermal history recorded during the bonding process is shown in Figure 7-4, which consists of five regimes, including I – preheating, II – loading, III – actuating, IV – holding, and V – releasing. Firstly, the pre-compressed substrates is heated up by the beneath fixture to a certain preheating temperature. Then the heating is paused, and the horn is moved down to press onto the substrates. The interfacial temperature will slightly decrease due to the heat transfer from the substrates into the horn. Once the loading pressure is triggered, ultrasonic vibration is generated and ultrasonic energy is transferred from the horn into the substrates, leading to temperature rising at the interface. After a short stage of temperature equilibrium, it starts to decrease with the decreasing pressure resulted from the slight separation between the further compressed substrates and the horn. It is believed that the further compression is due to the melting-free penetration of molecular chains across the interface, instead of bulk melting and weld penetration [245]. Then the ultrasonic actuation is ceased while the horn is held on the substrates for a few of seconds for cooling, during which the interfacial temperature decreases due to heat dissipation. Finally, the horn is lifted and the pressure is released.
Figure 7-4  Typical thermal history at the bonding interface with inset diagrams showing the five process regimes: I - preheating, II - loading, III - actuating, IV - holding and V - releasing.

The controlled processing parameters were trigger pressure ($P_t$), vibration amplitude ($A$), actuation time ($t$) and preheating temperature ($T_{hi}$). Both the trigger pressure and the vibration amplitude are associated with the processing pressure. The former one determines the initial static pressure, while the latter one can lead to dynamic processing pressure. In the previous works [247, 248], it was reported that higher pressure and higher vibration amplitude typically can
result in faster melting at the interface, while they are also effective in developing higher bond strength [170]. In order to avoid interfacial polymer melting, here we used low and constant trigger pressure (0.2 MPa). Very low amplitude (60%, 3.84 μm) was used by equipping a reverse booster (conversion ratio 1:0.8).

The preheating temperature can affect the polymer viscoelasticity and molecule mobility. In this study, the preheating temperature was set lower than the polymer nominal glass transition temperature ($T_g \approx 80^\circ$C). As shown in Figure 7-5, when the substrates were preheated to 75 °C, the interfacial temperature rose dramatically to 125 °C within 1 second and interfacial polymer melting was observed at the interface. It was reported that in ultrasonic bonding, when the interfacial temperature is close to the glass transition range, dramatic viscoelastic heating will dominate the heat generation resulting in rapid polymer melting [167]. Therefore, the preheating temperature should be lower than its glass transition temperature range to avoid the interfacial melting.
Figure 7-5  Effect of preheating temperature (at 50 °C, 60 °C and 75 °C) on the interfacial temperature during bonding process. Other parameters were kept constant at 0.2 MPa, 60 % and 10 s. The inset diagram shows the thermocouple position for temperature measurement.

With preheating temperature of 50 °C and 60 °C, the interfacial temperature was elevated moderately by about 10-12 °C, stabilized for about 5 seconds, and decreased slowly. It is also interesting to note that when the preheating temperature was 60 °C, the interfacial temperature can reach around 72 °C under ultrasonic actuation, but the interfacial polymer was free of melting. The possible reason could be that, the glass transition is a kinetic transition, and the viscoelastic properties of a thermoplastic change with both temperature and frequency. In this study, the glass transition temperature of COC was measured at various frequencies to investigate the effect of frequency on the glass transition temperature evolution. The $T_g$ measured by DSC was about 80 °C which
correlated fairly well with the results determined by DMA test at 1 Hz, as shown in Figure 7-6. This value is considered as the nominal glass transition temperature conventionally used in general polymer processing. However, when higher frequencies were applied in the DMA frequency sweep test, it is evident from Figure 7-7 that the storage modulus demonstrated higher values and the glass transition temperature shifted to a higher level. Therefore, at ultrasonic frequency of 35 kHz, the glass transition temperature was reasonably expected to be a few of degrees higher than 80 °C. When the interfacial temperature is still under the T_g at 35 kHz, the dramatic viscoelastic heating would not dominate the heat generation process, and the interfacial melting can be avoided.

The actuation time was also varied from 2 s to 10 s to control the energy input. It is evident from Figure 7-5 that, no less than 3 s was needed to reach the maximum interfacial temperature, and the effective equilibrium stage was found to be around 5 s. Therefore, the actuation time was chosen to be 10 s (the maximum controllable duration in time mode).
Figure 7-6 DMA results tested at 1Hz and DSC result in the inset graph.

Figure 7-7 DMA results of frequency sweep test from 0.2 Hz to 20 Hz. Only 6 out of 21 frequency sweep curves are plotted for figure clarity.
7.3.3 Bond strength enhancement

The bond strength was evaluated at various thermal bonding temperatures and preheating temperatures as shown in Figure 7-8. It is apparent that without ultrasonic actuation, the bond strength increases with increasing of temperature, but is generally low because of low pressure and short duration used in thermal bonding. The development rate of bonding is faster at higher temperatures, and is lower below the T_g due to sluggish molecular interdiffusion. This trend agrees well with the results reported in previous work [144].

When ultrasonic actuation was applied, it can be clearly identified from Figure 7-8 that the bond strength was enhanced to a higher level at each corresponding thermal bonding temperature. When the preheating temperature of 50 °C was used, the improvement in bond strength was minor, because the elevated interfacial temperature was only around 60 °C. With higher preheating temperature at 60 °C, the interfacial temperature can reach around 72 °C, at which the molecular chain segments can move more swiftly, and thereafter, the bond strength can be enhanced through accelerated interdiffusion.
Bond strength development and enhancement via ultrasonic actuation at preheating temperatures of 50 °C and 60 °C, compared to the control set with pure thermal bonding. Inset graph shows the typical tensile results of the samples in condition A (without ultrasonic actuation) and condition B (with ultrasonic actuation at preheating temperature of 60 °C).

It was reported that bonding at the polymer interface can be achieved through surface wetting and polymer chain interdiffusion [145]. In our case, the bond strength at the intimate contact was initially developed during thermal bonding through surface wetting and primeval polymer chain interdiffusion. As shown in Figure 7-9(a), this step has proven to be crucial to eliminate the surface asperities to avoid bonding defects described in earlier section. Once the two surfaces conform to each other, they can heal together by molecular interdiffusion and entanglement. However, after thermal bonding as shown in Figure 7-9(b), the bond strength was low, which could be attributed to that, the
interdiffusion of polymer molecules at the interface was inferior, the entanglement of molecular chains was incompact, and the bond strength was much lower than the bulk native strength. Therefore, when ultrasonic actuation was applied, the ultrasonic energy can mainly focus at the interface resulting in stimulated intermolecular friction. The interfacial temperature was elevated and interdiffusion of polymer chain segments were accelerated to a greater extend as shown in Figure 7-9(c). It is more straightforward to understand this mechanism in the viewpoint of a multi-step thermal bonding process. The bond strength at the thermally bonded interface can be further increased through several follow-up repetitions just because the polymer chain interdiffusion at the interface can be repetitively stimulated.

It also should be noted that when the thermal bonding temperature was much lower than 75 °C, insufficient intimate contact can lead to edge melting under ultrasonic actuation. On the other hand, for those substrates pre-bonded at temperature much higher than the T_g, the dimension integrity can be lost to a great extend due to microchannel collapse. When the preheating temperature was close to the T_g, interfacial melting was observed on the bonding interface. These above phenomena can help us to define the temperature processing window and should be taken into account especially in the application of microfluidic device bonding.
Figure 7-9  Schematic diagrams of (a) intimate contact and initial bond strength development through thermal bonding, and (b-c) molecular dynamic movement around/across the bonding interface in (c) thermal bonding with double-sided heating and static compression and (d) ultrasonic actuation with single-sided heating and ultrasonic oscillating compression.

Typical micrographs of the failure surfaces bonded after thermal bonding and after ultrasonic actuation were taken by SEM as shown in Figure 7-10. The failure surface in Figure 7-10(a) is not smooth, indicating the existence of molecular chain interdiffusion at the interface. It can be seen from Figure 7-10(b) that the surface is even rougher. The flaws at the failure surface indicate that under ultrasonic actuation, the polymer chains at the interface own significant interdiffusion to each other, which contributes to the improved bond strength.
The bonding results compared between several different bonding methods were summarized in Table 7-1. The results of pure thermal bonding indicate that when the microchannel integrity was desirably preserved, the bond strength (0.38 MPa) was lower compared to other methods. On the other hand, when a higher bonding temperature 85 °C ($T_g+5$ °C) was used, the bond strength (0.67 MPa) can be almost doubled whilst the microchannel deformation became unacceptable. According to the reptation theory, the developed bond strength is a function of the contact time to the fourth power [145]; therefore, when a multiple-step thermal bonding was conducted, the bond strength can be improved as the total bonding time was prolonged. However, the microchannel distortion was also noticeably increased at the same time. When an auxiliary ultrasonic actuation was applied at 60 °C after thermal bonding, the bond strength (0.69 MPa) is comparable to that obtained by pure thermal bonding at 85 °C ($T_g+5$ °C).
Moreover, the process duration is only a few seconds and the microchannel deformation is lower which will be analyzed in the following section.

<table>
<thead>
<tr>
<th>Bonding methods</th>
<th>Temperature</th>
<th>Time</th>
<th>Pressure</th>
<th>Strength</th>
<th>Deformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal bonding</td>
<td>75 °C</td>
<td>5 min</td>
<td>0.32 MPa</td>
<td>0.38±0.04 MPa</td>
<td>Medium</td>
</tr>
<tr>
<td></td>
<td>85 °C</td>
<td>5 min</td>
<td>0.32 MPa</td>
<td>0.67±0.05 MPa</td>
<td>Major</td>
</tr>
<tr>
<td>Thermal bonding × 3</td>
<td>75 °C</td>
<td>5 min×3</td>
<td>0.32 MPa</td>
<td>0.61±0.05 MPa</td>
<td>Major</td>
</tr>
<tr>
<td>Ultrasonic actuation after thermal bonding</td>
<td>60 °C</td>
<td>10 s</td>
<td>0.2 MPa</td>
<td>0.69±0.07 MPa</td>
<td>Minor</td>
</tr>
</tbody>
</table>

### 7.3.4 Negligible microchannel deformation

COC substrates with microchannel dimension of 200 μm × 200 μm were injection-molded and bonded with processing parameters listed in Table 7-1 for the microchannel deformation analysis. The typical cross-sectional profiles of the microchannel on BMG, the microchannel in COC after micro injection molding, after thermal bonding and after ultrasonic actuation were measured respectively by the confocal profilometer and compared in Figure 7-11(a-c). The microchannels in COC substrate were replicated from the BMG micromold with very good integrity. After thermal bonding, there is a medium depth loss by 12.4% (±0.7%) as typically shown in Figure 7-11(b). However, after the subsequent ultrasonic actuation, the additional dimensional loss in depth is only 3.2% (±0.3%) as typically shown in Figure 7-11(c). A bonded sample is shown in Figure 7-11(d) and a cross-sectional micrograph of the sealed microchannel is shown in Figure 7-11(e). The profile distortion in the SEM micrograph was resulted from sample
cross-sectioning including cutting with a diamond cutter and polishing with diamond pastes, which may not exactly present the microchannel dimension after bonding. The possible reason for the negligible microchannel deformation could be that, the ultrasonic energy mainly focuses at the bonding interface, while the temperature of the bulk polymer is still quite lower than its elevated glass transition temperature at ultrasonic frequency. It is known that, for a given temperature, the Tan δ (loss modulus over storage modulus) indicates which deformation is dominant [184]. From Figure 7-7, the Tan δ decreases with increasing of frequency, indicating that the viscous components of COC decrease at a certain temperature. Therefore, the dimension of microchannel can be well retained during ultrasonic actuation.

![Figure 7-11](image)

Figure 7-11  (a-c) Comparison of typical microchannel profiles, (d) photo of a bonded COC chip and (e) SEM micrograph of a cross-sectional sealed microchannel.
7.4 Conclusion

In this chapter, a rapid bonding enhancement method has been proposed and applied to a COC microfluidic device. The primary bonding prerequisite has been found to be the proper intimate contact between the bonding surfaces. With improper intimate contact, several bonding defects, such as localized spot welding, voids and edge melting would occur. A straightforward thermal bonding has been used to achieve the intimate contact, which can also initiate the bond development through surface wetting and primeval polymer interdiffusion with relatively weak bond strength. With auxiliary ultrasonic vibration, the bond strength can be significantly improved within remarkable short time (less than 10 s), compared to that obtained by pure thermal bonding. The enhancement in bond strength could be attributed to the re-stimulated and accelerated molecular chain interdiffusion across the bonding interface under ultrasonic actuation. The enhanced interdiffusion could be due to the elevated interfacial temperature by the transmitted ultrasonic energy, together with the oscillating bonding pressure instead of a static compression pressure. The bond strength obtained at a preheating temperature of 20 °C lower than the glass transition temperature can be comparable to the strength by a pure thermal bonding at temperature 5 °C higher than the \( T_g \). Moreover, the microchannel deformation has been analyzed and found to be negligible, which could be due to the increase in glass transition temperature at ultrasonic frequency confirmed by dynamic mechanical analysis.
Chapter 8  Conclusions and Future Work

8.1 Concluding remarks

In this thesis, we have presented an applicable process flow for fabrication of thermoplastic microfluidic devices, including micromold fabrication, substrates replication, and device bonding. Major research efforts have been made to fulfill the two proposed objectives: (1) to investigate and study the micro injection molding process for high-fidelity and low-stress replication using robust BMG micromold; and (2) to investigate and study novel bonding technologies to improve the bond strength and microchannel dimensional integrity of thermal bonding.

We have designed a universal platform substrate, which is highly flexible to develop microfluidic devices with various designs and convenient for chip-to-world interconnection by easy tubing connection. Several specific molding tools with easy replacement of micromold were used to fabricate two types of microfluidic substrates, the platform substrates and the plain flat substrates. Silicon micromold was fabricated by photolithography and deep reactive-ion etching technologies to obtain high resolution microstructures (minimum critical dimension was 20 μm). The robust metallic micromold made of Zr-based bulk metallic glass was fabricated from the sacrificial silicon primary micromold by micro hot embossing. In order to replicate microchannels with high fidelity, a
Taguchi design of experiment on micro injection molding with the embossed BMG micromold was conducted, and the effects of micro injection molding processing parameters on replication fidelity were studied.

Despite that microchannels can be replicated with high-fidelity by optimized micro injection molding process, the injection-molding-induced residual stresses around microchannels were overlooked in the earlier experiments. We have observed that the molded residual stress can lead to irregular and asymmetric deformation in well-formed microchannel during direct thermal bonding process. This phenomenon is more evident in microchannels aligned perpendicular to the polymer melt injection direction. Design of experiment on micro injection molding re-optimization was carried out to reduce the residual stresses in order to achieve the lowest microchannel deformation irregularity. We have proposed that direct thermal bonding and photoelastic stress analysis in terms of phase retardation are feasible non-destructive methods to qualitatively evaluate the status and effects of residual stresses. The dominant molding parameters with positive effects were found to be higher melt temperature, higher mold temperature and prolonged cooling time after holding. With improved molding condition, the residual stresses around microchannels aligned perpendicular to the molding direction can be moderated.

Thermal bonding is a straightforward, inexpensive and widely-used method to homogeneously bond thermoplastic substrates. However, the trade-off between high bond strength and low microchannel deformation is always a
crucial consideration. A novel, low-temperature and deformation-free thermal bonding method was proposed to seal hydrophilicity-stable PMMA microchannels. Oxygen plasma pre-/post-treatments and polyvinyl alcohol (PVA) coating were performed on the PMMA microfluidic substrates before thermal bonding. Different surface treatments were characterized by confocal profilometer, tensiometer, attenuated total reflection Fourier-transform infrared spectrometer, differential scanning calorimeter, and scanning electron microscope. The effects of surface modifications on bond strength and microchannel integrity were studied. Oxygen plasma pre-treatment was found to be significant in improving the coating uniformity and enhancing the adhesion between PVA layer and PMMA base. The PMMA microchannel substrate can be bonded to a homogeneous PMMA cover plate at about 70 °C (30 °C lower than the T_g of PMMA) with the coated PVA layer serving as a medium material which had high wettability, high surface energy and low T_g. With oxygen plasma post-treatment of the coated PVA layer, the bond strength was improved and comparable to that obtained by pure thermal bonding at a temperature near the T_g of PMMA. Due to the low bonding temperature, the microchannel integrity was well retained with negligible deformation. The hydrophilicity stability of different surface treatments was evaluated and compared under both dry and wet storage conditions for a month, which suggested that the PVA-coated PMMA substrates with oxygen plasma post-treatment present the highest hydrophilicity and lowest hydrophobic recovery. As a demonstration, monodispersed oil-in-water (O/W) droplets with volume of sub-10 nL were
successfully and reliably generated in the hydrophilic microfluidic devices fabricated with the proposed bonding method.

Ultrasonic bonding is a promising method to achieve high bond strength and low microchannel deformation. We have observed that it was impossible to directly ultrasonically bond thermoplastic substrates at low temperature without a prior intimate contact between bonding surfaces. With improper contact, several bonding defects would occur, such as voids, localized spot melting and edge melting. We have investigated the effects of auxiliary ultrasonic actuation on thermally-bonded interface, and proposed an effective method for bond strength enhancement while keeping the microchannel integrity. Under auxiliary ultrasonic vibration within 10 seconds, the bond strength obtained at a preheating temperature of 20 °C lower than the T_g can be enhanced which was comparable to the strength of pure thermal bonding at 5 °C higher than the T_g. It was found that the introduced ultrasonic energy elevated the interfacial temperature, which can facilitate the interdiffusion of molecular chain segments at the bonding interface. The microchannel deformation after ultrasonic actuation was found to be negligible. Dynamic mechanical analysis was conducted to evaluate the effect of ultrasonic frequency on glass transition temperature. It was found that the increased T_g at ultrasonic frequency was still higher than the temperature of bulk polymer under ultrasonic actuation; therefore, undesirable microchannel deformation can be avoided.
The key contributions of this thesis are summarized as below:

(1) Evaluation and reduction of the effects of residual stresses induced in injection molding on microchannel integrity during thermal bonding.

(2) Study of a novel bonding method to improve the bonding performance and chip functionality, by reliable surface modifications via oxygen plasma treatment and PVA coating.

(3) Study of the effects of auxiliary ultrasonic actuation on bond strength enhancement after thermal bonding.

8.2 Recommendations for future work

In this thesis, the fabrication limit of feature dimension was restricted by the printing resolution and critical dimension (20 μm) of the plastic transparency mask used in ultraviolet photolithography. As sub-10 μm or even nano-scaled features are highly desired in microfluidic device for biomolecular applications, it is necessary to use high resolution mask and lithography techniques, such as electron beam lithography (EBL) and ion beam lithography (IBL). Moreover, the microstructures fabricated in this thesis were mainly microchannels and reservoirs with aspect ratio (defined as the height/width value) less than 2. Higher aspect ratio microstructures, such as micropillars and microwells are also frequently used in microfluidic devices. They can be easily fabricated by PDMS-based soft lithography, but for micro injection molding, it remains a challenge
Therefore, it is necessary to establish a reliable molding process with robust tools to address this issue.

Further investigation on molded-in residual stress in injection-molded thermoplastic substrates could be conducted. Advanced molding tools can be applied to further reduce the residual stresses. Theoretically there will be no flow-induced residual stress if the entire filling stage is isothermal and longer than the longest polymer relaxation time [206]. Therefore, a variotherm mold can be used to isothermally adjust the mold temperature around $T_g$ in a wide range. Moreover, further assessment on molded-in residual stress in terms of principal stress difference can be achieved through full-scale calibration on both stressed material and optic components, and through quantitative calculation based on stress-optic coefficient, principal-stress directions and phase retardation.

In the study of low-temperature bonding with surface modifications, more studies could be carried out, such as the effect of solution concentration on coating efficiency and the quantitative measurement of coating adhesion strength. Except oxygen plasma and PVA, it would be valuable if other types of plasma and other hydrophilic, water-soluble and low-$T_g$ polymers that contain polar or charged functional groups can be applied and investigated. The potential plasma may include nitrogen plasma, argon plasma and hydrogen plasma. The potential alternative coating polymers may include poly acrylic acid (PAA) and polyvinyl pyrrolidone (PVP). Moreover, this bonding method should be applied to other thermoplastics with different grades of glass transition temperatures, such as COC series.
In this thesis, the interfacial temperature variation under ultrasonic actuation was measured by a pre-embedded sheathed thermocouple with junction-tip diameter of 197.8 (±11.2) μm. Though this method has been adopted in many related works [167, 170, 250-253], several technical issues have been overlooked, such as vibration and movement of the embedded thermocouple joint, friction between the thermocouple joint and the surrounding polymer. In fact, it is exceedingly difficult to obtain accurate measurement of interfacial temperature under ultrasonic vibration. Therefore, alternative non-contacting measurement should be tried in the future work, such as using an infrared radiation thermometer minutely in the direction perpendicular to the interface through a bottom transparent NaCl single crystal window [254], though this method is also limited to the sensitivity to the thickness of polymer film. Moreover, other potential pre-bonding method can be tried in order to achieve proper intimate contact as well as low microchannel deformation, such as UV/ozone surface modification [139].
Appendix

A1. MATLAB program for phase retardation calculation

```matlab
%input the images of the transmitted light collected over one
complete rotation of the analyzer
i1=double(imread('H:\PhD Research\2_Mesurement results\3_Phase shift polariscope\20131019\2.0.tif'));
i2=double(imread('H:\PhD Research\2_Mesurement results\3_Phase shift polariscope\20131019\2.45.tif'));
i3=double(imread('H:\PhD Research\2_Mesurement results\3_Phase shift polariscope\20131019\2.90.tif'));
i4=double(imread('H:\PhD Research\2_Mesurement results\3_Phase shift polariscope\20131019\2.135.tif'));

l=(i1+i2+i3+i4)/4;

%calculate the orientation of the fast axis
k=0.5*(atan2(i3-i1,i2-i4+eps));

%calculate the phase retardation
s=sqrt(((i3-i1).^2)+((i4-i2).^2))/(2.*l+eps);
delta=asin(s)*(180/pi)-1.918;

%calculate the Ica and Isa
Ica=(-s).*sin(2*k);
Isa=s.*cos(2*k);

figure;imagesc(Ica);axis off; colorbar; caxis([-0.4 0.6]);
xlim([505 1055]); ylim([53 603]);
title('Ica');

figure;imagesc(Isa);axis off; colorbar; caxis([-0.4 0.6]);
xlim([505 1055]); ylim([53 603]);
title('Isa');

k=k*(180/pi);
figure;imagesc(k); axis off; colorbar; caxis([-90 90]);
xlim([505 1055]); ylim([53 603]);
title('Orientation of fast axis');

figure;imagesc(abs(delta)); axis off; colorbar; caxis([0 45]);
xlim([505 1055]); ylim([53 603]);
title('Phase retardation');
```

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References


Kuo J S and Chiu D T 2011 Disposable microfluidic substrates: Transitioning from the research laboratory into the clinic Lab Chip 11 2656-65

De Mello A 2002 Plastic fantastic? Lab Chip 2 31N-6N


Becker H and Gärtner C 2000 Polymer microfabrication methods for microfluidic analytical applications Electrophoresis 21 12-26


Tsao C W and DeVoe D L 2009 Bonding of thermoplastic polymer microfluidics Microfluid. Nanofluid. 6 1-16


Heckele M, Bacher W and Müller K D 1998 Hot embossing - The molding technique for plastic microstructures Microsyst. Technol. 4 122-4


Pfleging W, Przybylski M and Brückner H J 2006 Excimer laser material processing - State of the art and new approaches in microsystem technology. (San Jose, CA

[41] Schaller T, Bohn L, Mayer J and Schubert K 1999 Microstructure grooves with a width of less than 50 μm cut with ground hard metal micro end mills Precision Engineering 23 229-35


[64] Browne D J, Stratton D, Gilchrist M D and Byrne C J 2013 Bulk metallic glass multiscale tooling for molding of polymers with micro to nano...


[68] Pan C T, Wu T T, Chang Y C and Huang J C 2008 Experiment and simulation of hot embossing of a bulk metallic glass with low pressure and temperature J. Micromech. Microeng. 18 025010


[75] Lewandowski J J, Wang W H and Greer A L 2005 Intrinsic plasticity or brittleness of metallic glasses Philosophical Magazine Letters 85 77-87

[76] Murali P and Ramamurty U 2005 Embrittlement of a bulk metallic glass due to sub-Tg annealing Acta Materialia 53 1467-78


[80] Henann D and Anand L 2008 A constitutive theory for the mechanical response of amorphous metals at high temperatures spanning the glass transition temperature: Application to microscale thermoplastic forming Acta Materialia 56 3290-305


[86] Kumar A and Whitesides G M 1993 Features of gold having micrometer to centimeter dimensions can be formed through a combination of stamping with an elastomeric stamp and an alkanethiol "ink" followed by chemical etching Applied Physics Letters 63 2002-4


[106] Young Hak C, Young Soo S, In Yong M, Bo Hyun K and Keun P 2013 Facile fabrication of superhydrophobic poly(methyl methacrylate) substrates using ultrasonic imprinting J. Micromech. Microeng. 23 055019


Huang F C, Chen Y F and Lee G B 2007 CE chips fabricated by injection molding and polyethylene/thermoplastic elastomer film packaging methods *Electrophoresis* **28** 1130-7


Kelly R T, Pan T and Woolley A T 2005 Phase-changing sacrificial materials for solvent bonding of high-performance polymeric capillary electrophoresis microchips *Anal. Chem.* **77** 3536-41


distortion, high-strength bonding of thermoplastic microfluidic devices employing case-II diffusion-mediated permeant activation *Lab Chip* 7 1825-31


[142] Koesdjojo M T, Tennico Y H and Remcho V T 2008 Fabrication of a microfluidic system for capillary electrophoresis using a two-stage embossing technique and solvent welding on poly(methyl methacrylate) with water as a sacrificial layer *Anal. Chem.* 80 2311-8


[147] Li J, Chen D and Chen G 2005 Low-temperature thermal bonding of PMMA microfluidic chips *Analytical Letters* 38 1127-36


Chen Z, Zhang L and Chen G 2010 A spring-driven press device for hot embossing and thermal bonding of PMMA microfluidic chips *Electrophoresis* 31 2512-9


Park T, Song I, Park D S, You B H and Murphy M C 2012 Thermoplastic fusion bonding using a pressure-assisted boiling point control system *Lab Chip*


[172] Bhattacharya S, Datta A, Berg J M and Gangopadhyay S 2005 Studies on surface wettability of poly(dimethyl) siloxane (PDMS) and glass under oxygen-plasma treatment and correlation with bond strength *Journal of Microelectromechanical Systems* 14 590-7


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Bhattacharyya A and Klapperich C M 2007 Mechanical and chemical analysis of plasma and ultraviolet-ozone surface treatments for thermal bonding of polymeric microfluidic devices Lab Chip 7 876-82


Wang Y, Chen H, He Q and Soper S A 2008 A high-performance polycarbonate electrophoresis microchip with integrated three-electrode system for end-channel amperometric detection Electrophoresis 29 1881-8


Jokinen V, Suvanto P and Franssila S 2012 Oxygen and nitrogen plasma hydrophilization and hydrophobic recovery of polymers Biomicrofluidics 6


[187] Li C, Yang Y, Craighead H G and Lee K H 2005 Isoelectric focusing in cyclic olefin copolymer microfluidic channels coated by polyacrylamide using a UV photografting method Electrophoresis 26 1800-6


[192] Ng S H, Wu Y and Wang Z 2010 Corona discharge assisted thermal bonding of polymer microfluidic devices Microsyst. Technol. 16 1181-6


Yang Y, Li C, Kameoka J, Lee K H and Craighead H G 2005 A polymeric microchip with integrated tips and in situ polymerized monolith for electrospray mass spectrometry Lab Chip 5 869-76


[225] Zhang Y, Ping G, Kaji N, Tokeshi M and Baba Y 2007 Dynamic modification of poly(methyl methacrylate) chips using poly(vinyl alcohol)
for glycosaminoglycan disaccharide isomer separation Electrophoresis 28 3308-14


[231] Beattie J K 2006 The intrinsic charge on hydrophobic microfluidic substrates Lab Chip 6 1409-11

[232] Cassu S N and Felisberti M I 1997 Poly(vinyl alcohol) and poly(vinyl pyrrolidone) blends: Miscibility, microheterogeneity and free volume change Polymer 38 3907-11


[234] Chen Y, Zhang L and Chen G 2008 Fabrication, modification, and application of poly(methyl methacrylate) microfluidic chips Electrophoresis 29 1801-14


[238] Wu H, Huang B and Zare R N 2005 Construction of microfluidic chips using polydimethylsiloxane for adhesive bonding Lab Chip 5 1393-8


[240] Arayanarakool R, Le Gac S and van den Berg A 2010 Low-temperature, simple and fast integration technique of microfluidic chips by using a UV-curable adhesive Lab Chip 10 2115-21


