A Rapid Bonding Method for Fabricating Mixing Microfluidic Chip Based on Micromachining Technology

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In this paper, a rapid bonding method is reported to fabricate a mixing microfluidic chip. The chip is composed of a glass upper plat and a polyurethane bottom plat. The upper plat with a microchannel is obtained through micromachining technology. And the bottom plat is manufactured via mixing the solution with the component of isocyanic acid and polyether polyol. The influence of the solution’s proportion on the contact angle and bonding force is investigated to enhance the hydrophilicity and the bonding strength. Furthermore, a mixing experiment is implemented to verify the chip’s bonding effect. The experimental results demonstrate that with increasing the proportions of isocyanic acid and polyether polyol, the contact angle and the bonding force increase at first and then decrease gradually. That is attributed to the variation of internal porous structure for different proportions. Considering the contact angle and the bonding force synthetically, the optimal proportion of 3.7 w/w is confirmed. The mixing efficiency is increased from 0.157 to 0.824. Compared with other bonding methods, the method in this paper has the advantages of high efficiency and high bonding strength.

1. Introduction

Microfluidic chips [1] with microchannel, micropump, microvalve, and other units have been widely applied [2] to DNA analysis, immunoassay, and so on, owing to the main feature of rapidity, high efficiency, and low consumption [3, 4]. Among them, a mixing microfluidic chip [5] is utilized to realize the functions including rapid mixing and analysis. Remarkably, due to its excellent performance, the mixing microfluidic chip has applications in such fields as biological analysis and chemical detection [6]. Furthermore, in order to obtain the chips with different substrates, the technologies including channel fabricating [7] and chip bonding [8] are investigated.

Thereinto, the bonding [9] is a crucial processing step [10]. Currently, a variety of bonding methods [11] are employed to achieve the bonding of the different materials including glass/silicon, glass/glass, glass/PDMS, PDMS/PDMS, and PMMA/PMMA. To be noted, due to different properties of the material, the complexity for different bonding methods is not inconsistent [12, 13]. For instance, an anodic bonding method is adopted to achieve the bonding of glass/silicon [14]. Nonetheless, an electrostatic bonding machine with the expensive value is essential. Remarkably, the simple bonding machine is used to implement the bonding of PMMA/PMMA [15], whereas the crack is more likely to happen owing to the lack of bonding strength. Dramatically, the bonding of glass/glass [16] compensates for the insufficiency of the former. A two-step bonding method including prebonding bonding and hot bonding is utilized to enhance the bonding strength. Regrettably, the low success rate of prebonding has become a bottleneck restricting its rapid development [17]. Fortunately, the plasma-assisted hot bonding is employed to improve the bonding success rate of glass/PDMS and PDMS/PDMS [18]. Nevertheless, the above methods require a bonding time [19] of at least half an hour. Accordingly, a rapid bonding method of the glass and polyurethane needs to be further investigated for fabricating mixing microfluidic chips.

In this paper, the bonding of glass/polyurethane is accomplished to manufacture mixing microfluidic chip through micromachining technology. Based on the chip, the influence of the solution’s proportion on the contact...
angle and bonding force is analyzed to enhance the hydrophilicity and the bonding strength of mixing microfluidic chip. At the end of the article, the mixing experiment of the deionized water and the blue ink is demonstrated to verify the bonding effect.

2. Mixing Experiment Preparation

The mixing microfluidic chip is composed of a glass upper plat and a polyurethane bottom plat. The glass plat with a layer of chromium is adopted to fabricate the upper plat. And the schematic illustration of the fabrication process is exhibited in Figure 1. The detailed steps are as follows: ① exposure for about 60 s, ② development for about 10 s, ③ wet etching for chromium, ④ wet etching for glass, ⑤ ultrasonic drilling, and ⑥ removing surface residual. The bottom plat is established by mixing the isocyanic acid and the polyether polyol with certain proportions. And that is located in the oven with 40°C for 30 min.

The bottom plat is manufactured via mixing the solution with the component of isocyanic acid and polyether polyol. And then, the upper plat and the bottom plat are confined together to form the mixing microfluidic chip, as shown in Figure 2. It can be seen that the microchannel with the width of 100 μm and the depth of 30 μm has an acute angle of 30°. In addition, the diameter of the three reservoirs is 2 mm.

Based on the above mixing microfluidic chip, the deionized water and the blue ink are injected simultaneously into the microchannel of the chip utilizing the LSP02-2B Dual Channels Syringe Pump for the mixing experiment. The mixed images of different moments are taken for analyzing the mixing effect. In this section, the schematic diagram of the bonding and the injection process is shown in Figure 3.

3. Analysis and Discussion

3.1. Contact Angle. In order to estimate the performance of the mixing microfluidic chip (i.e., its hydrophilicity), the contact angle is selected as a measurement standard. And the effect of the proportions of isocyanic acid and polyether polyol on contact angle is investigated, as shown in Figure 4(a). It can be seen that the contact angle increases at first and then decreases gradually with increasing the proportions of isocyanic acid and polyether polyol. Specifically, the isocyanic acid and the polyether polyol are mixed with a certain percentage to form the polyurethane of porous structure [20, 21]. Furthermore, the number of holes increases with increasing the...
A rougher surface and larger contact angle. Taking the proportion of 3.4 w/w as an example, the contact angle is the largest, but the hydrophilicity of the chip surface is the worst. Remarkably, when the proportions of isocyanic acid and polyether polyol is in the range of 3.8 to 4.0 w/w, the contact angle turns out to be the smallest and the surface hydrophilicity is the best. A smaller contact angle will make it easier for the detected liquid passing into the microchannel. The photographs of contact angle with different proportions (3.2 w/w, 3.4 w/w, 3.8 w/w).

**3.2. Bonding Force.** The bonding is a crucial processing step. Furthermore, the bonding quality depends mainly on the proportion of isocyanic acid. And that leads to a rougher surface and larger contact angle. Taking the proportion of 3.4 w/w as an example, the contact angle is the largest, but the hydrophilicity of the chip surface is the worst. Remarkably, when the proportions of isocyanic acid and polyether polyol is in the range of 3.8 to 4.0 w/w, the contact angle turns out to be the smallest and the surface hydrophilicity is the best. A smaller contact angle will make it easier for the detected liquid passing into the microchannel. The photographs of contact angle with different proportions are exhibited in Figures 4(b)–4(d). And the schematic diagram of the relationship including the number of holes, surface roughness, contact angle, and hydrophilicity is shown in Figure 5.
bonding force between the substrate and the cover. In other words, the higher the bonding force is, the better the bonding quality is, and the better the seal performance of the chip is. In order to estimate the performance of the mixing microfluidic chip (i.e., its bonding quality), the bonding force is selected as another measurement standard. And then, the effect of the proportions of isocyanic acid and polyether polyol on bonding force is investigated, as shown in Figure 6(a). To be noted, the bonding force increases firstly and then decreases with increasing the proportion of isocyanic acid and polyether polyol. The reason for this phenomenon is the same as that of the contact angle. It is worth mentioning that when the proportion of isocyanate and polyether polyols is 3.6 w/w, the bonding force is the largest. In addition, the bonding forces with different proportions are shown in Figures 6(b)–6(d), and the measuring method of the bonding force is depicted in Figure 6(e). Considering the contact angle and the bonding force synthetically, the optimal proportion of 3.7 w/w is confirmed.

3.3. Mixing Efficiency. The deionized water and the blue ink are utilized to implement the mixing experiment. In order to investigate the mixing characteristics of the two solutions, equation (1) and equation (2) are introduced to evaluate the mixing effect. In equation (1), the concentration value $Y$ is obtained through bringing the gray value $X$. The gray values for 26 s, 30 s, and 34 s are 241, 203, and 188, respectively.

$$Y = 357.28661 - 2.50297X + 0.00437X^2. \quad (1)$$

From equation (2), $I_N$, defined in [22] as the concentration mixing index is calculated to estimate the mixing.
efficiency through bringing the concentration value \( Y \). In general, the higher the mixing index is, the better the mixing efficiency is.

\[
I_N = 1 - \frac{1}{50\%} (Y - 50\%).
\]

(2)

The relationship between the mixing index and the time is demonstrated in Figure 7(a). It can be seen that the mixing index increases over time. For instance, the corresponding mixing index at 26 s, 30 s, and 34 s are 0.157, 0.586, and 0.824, respectively. To be noted, when the time is more than 30 s, the growth rate of the mixing index is higher than that 30 s ago. That is attributed to the promoting effect of the acute angle channel (i.e., 30°). The mixing efficiency is also related to the channel structure. In addition, the mixing pictures at 26 s, 30 s, and 34 s are shown, respectively, in Figures 7(c)–7(e). Among them, three gray values corresponding to the three points are exhibited in Figure 7(b).

### 3.4. Comparison of Bonding Methods of Different Materials

Some bonding methods of different materials are listed in Table 1. It is worth noting that from the point of view of the bonding device, except for the method described in this article, other methods require specific devices to achieve bonding [23–25]. As for the bonding step, glass/glass [16], glass/PDMS, and PDMS/PDMS [18] require two steps for the bonding, while glass/silicon [14], PMMA/PMMA [15], and glass/polyurethane require only one step. From the perspective of bonding time [19], for all materials except glass/polyurethane, it takes 30 minutes or more. To be noted, for glass/polyurethane, it only takes 2 minutes. Through a comprehensive comparison of the above three aspects, the glass/polyurethane rapid bonding method avoids the problems of equipment utilizing and long bonding time. In summary, the proposed bonding method in this paper has the advantages of direct bonding, simple bonding step, and short bonding time.

### 4. Concluding Remarks

In order to manufacture mixing microfluidic chip, a rapid bonding method based on a micromachining technology is proposed. The influences of the proportions of the mixed...
solution on contact angle and bonding force are investigated to obtain the optimal proportion. Furthermore, a mixing microfluidic chip is fabricated based on the optimal proportion of mixed solution. The results of the mixing experiment demonstrate that with increasing the proportions of isocyanate and polyether polyol, the contact angle and the bonding force increase at first and then decrease gradually. Considering the relevant parameters including contact angle and bonding force comprehensively, the optimal proportion turns out to be 3.7 w/w. The mixing experiment results show that the mixing efficiency is increased from 0.157 to 0.824 over time. In summary, a rapid bonding method of mixing microfluidic chip has the characteristics of high efficiency and high bonding strength.

**Data Availability**

The (data type) data used to support the findings of this study are included in the article. Some of the important data supporting the conclusions of the study are shown in Figures 4, 6, and 7.

**Conflicts of Interest**

The authors declare no conflicts of interest.

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