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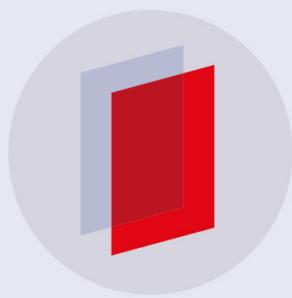
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Fabrication of polymer via holes by a combination of hot embossing and indentation processes

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Abstract

In this paper, a new fabrication approach of a polymer micro via hole array on a large area substrate is presented by a combination of hot embossing and indentation processes. Polymer via holes were formed by hot embossing, and opened by an indentation process. An aluminum alloy buffer layer, as a receptor of pins on a stainless steel mold due to the low hardness of aluminum, was used to support a polymer sheet. The via hole array was fabricated by a sequential process of hot embossing and indentation. Polymer micro via hole arrays 100 μm to 1.0 mm in diameter were fabricated on a 10 cm \times 10 cm area successfully. This facile approach is promising for a low-cost mass fabrication of polymer micro via arrays on a large area substrate.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The micro via hole is one of the critical components in polymer microelectromechanical systems (MEMS) for microfluidics [1], bio-chips [2, 3], light-emitting devices [4], etc. A via hole on a millimeter scale can be fabricated in high quality by conventional machining processes since it is easy to machine polymer materials. However, the polymer fabrication becomes intractable when the feature size drops to the microscale. Thus the fabrication of polymer micro via holes has attracted increasing research interest in the past few decades. Various methods were investigated including laser ablation [5, 6], mechanical drilling [7, 8], punching [9–13], etc. Laser ablation can fabricate via holes promptly. The diameter and depth of hole are determined by the laser beam size and energy. Some commercial laser processes can fabricate a polymer via hole with diameter and depth of 10 and 120 μm , respectively. Mechanical drilling is another easy way for via holes with fixed diameter. The minimum diameter of via holes fabricated using some commercial drilling machines reaches 50 μm . This size can meet some requirements in MEMS applications. Punching is another rapid process for various materials including polymer [12–15] and metal [9, 10]. Joo

[10] reported punching of via holes of 25 μm diameter in metal foils by tungsten carbide tool sets. The above fabrication methods demonstrate flexible process capabilities for polymer via holes on a microscale with a relatively low yield.

In recent years, there has been increasing demand on mass fabrication of a polymer micro via hole array on a large area for MEMS devices. For example, a dispensing well plate device requires hundreds of micro via holes on an area of 6 inch diameter [3]. The previous fabrication methods still need further improvements for mass fabrication of polymer via holes on a large area. Otherwise it is difficult for laser drilling and mechanical drilling to fabricate holes simultaneously. Alignment is also needed for the fabrication of polymer via hole arrays. These operations result in a low yield or a low efficiency. Punching can be taken as a parallel operation if there are enough punching tools. However, it has a critical demand on alignment with a small clearance between pin and receptor edges. A large clearance may cause a rough edge on the hole.

Regarding low-cost mass fabrication, hot embossing is a promising approach [14–16] for micro via arrays. One of the main challenges is how to remove the thin residual layer on the bottom, even if the thickness is only tens of microns.

Several ways were investigated to meet the demand. Gurung [16] used fly cutting to open via holes by removing a thin layer thicker than the residual layer. Rapp [15] demonstrated another approach using a double side hot embossing process. A secondary polysulfone (PSU) mold, replicated from the primary mold by hot embossing, served as a receptor for pins on the primary mold since it has much higher glass transition temperature (T_g) than polymethyl methacrylate (PMMA). Before embossing, the PMMA sheet was sandwiched by the primary mold and the secondary polymer mold. They were heated above the T_g of PMMA, but below the T_g of PSU. The pin on the primary mold was pressed into the PMMA sheet until it reached the PSU trench mold. As a result, the residual layer is pushed into the receptor. Compared to other punching processes, this new approach needs no alignment. But there is still a possible tiny clearance between the pin and receptor due to thermal expansion of metal and polymer materials at different process temperatures. In fact, even a tiny clearance may cause rough edges on a via hole.

Here a facile approach to open micro via holes by indentation during the hot embossing process is presented. The residual layer is removed by the indentation between hard pins and a soft buffer layer beneath the polymer substrate. There is no clearance between the pin and the receptor. Through this approach, various polymer micro via hole arrays were hot embossed on a large area in half an hour.

2. Experiments

The fabrication process of polymer via holes demonstrated in this paper mainly consists of two stages: forming blind micro holes by hot embossing, and removing a residual layer by indentation, as shown in figure 1. Compared to conventional experimental setups, only an Al alloy film is used as an additional buffer layer with lower hardness than the mold insert, but with much greater hardness than polymer materials in the molding stage. The polymer sheet and the metal buffer layer are sandwiched by the mold insert and the bottom hot plate, as shown in figure 1. After they are heated up to a molding temperature, the pins on the mold insert are pressed into the polymer to form blind holes with a thin residual layer left on bottom. Next they are continuously pressed into the buffer layer as an indentation with a depth greater than the thickness of the residual layer. The residual layer is removed by the pins and the sidewall of indents. Therefore the via hole array is opened in this continuous operation during a single cycle of the conventional hot embossing process.

2.1. Materials

Various polymers can be used in this fabrication process. Here commercial PMMA and polypropylene (PP) are selected for demonstration because they have been routinely used in hot embossing. PMMA and PP sheets of 0.5 mm thickness were baked at 80 °C in an oven for 5 h before hot embossing. This long bake is supposed to dry the polymer and prevent air bubbles during the embossing process. An Al alloy film was used as a buffer layer as an indentation

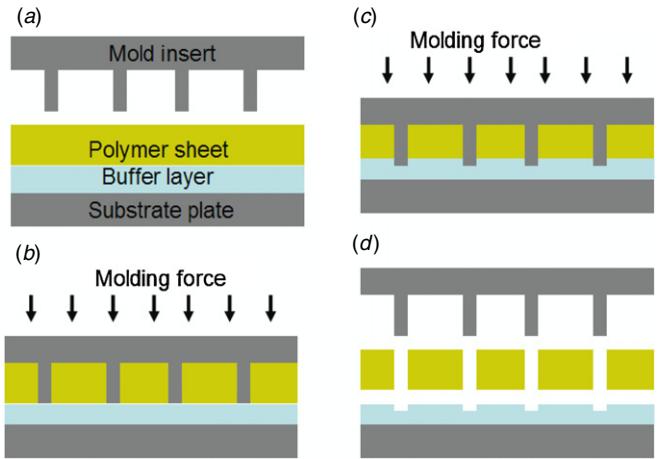


Figure 1. Sketch of fabrication of polymer via hole by a combination of indentation and hot embossing processes: (a) polymer sheet and buffer layer are sandwiched by the rigid substrate plate and the mold insert with pins; (b) the pins are pressed into the polymer with a thin residual layer left on the bottom of the blind hole; (c) the pins are pressed down into the polymer and onto the buffer layer, ending in an indent with a depth greater than the thickness of the residual layer. The polymer residual layer is cut by the pins and sidewall of indents, and pressed into the bottom of the indentation; (d) opened via holes.

receptor for pins on a mold insert. The Al alloy 1100 sheet (McMaster-Carr, USA) of 0.5 mm thickness has a hardness of Brinell 23. Nickel has a normal hardness of Brinell 90 to 140 [17]. The mismatched hardness promises protection of the pins on the mold insert during the fabrication process. Al alloy sheets were polished to reduce the roughness.

2.2. Hot embossing machine

The hot embossing process is performed in HEX01 (JENOPTIK, Germany). There are two hot plates in this machine: a bottom stationary and a top movable hot plate. The maximum force and temperature are 50 kN and 320 °C, respectively. A rotary pump is connected to an embossing chamber to provide vacuum lower than 0.1 mbar.

2.3. Mold inserts

Two mold inserts were designed: electroformed nickel round pin array of 100 to 800 μm diameter and 50 μm height, and computer numerically controlled (CNC)-machined stainless steel square pin array of 1 mm side length and 1 mm height.

The nickel mold insert was fabricated through UV lithography and the electroforming process, which are parts of standard UV-LIGA [8, 18, 19]. SU8 3050 photoresist (MicroChem, USA) was spin coated on a 4 inch silicon wafer with a Cr/Au (50/100 nm) seed layer, soft baked at 95 °C for 15–30 min, and exposed to UV light at dose of 250–300 mJ cm⁻² in a Karl Suss MA6 mask aligner (Karl Suss, Germany) using a printed mask (CAD Art Service, USA). Then it was post baked at 95 °C for 5 min, and developed in propylene glycol monomethyl ether acetate (Sigma-Aldrich, USA). The patterned SU8 photoresist was used as a mold for

Table 1. Hot embossing parameters.

Process parameter	Value
Molding temperature	190 °C
Molding force	30 kN on 10 × 10 cm ² area
Molding time plus indentation	10 min
Demolding temperature	85 °C

electroplating. Three millimeter thick nickel was deposited at a direct current of 2.0 A in a plating station SE101 (Digital Matrix, USA). The electroformed nickel mold insert was machined to adapt the work holder in the hot embossing machine. Finally, the SU8 was removed using SU8 remover (MicroChem., USA).

2.4. Hot embossing process

The hot embossing process is optimized to mold the blind hole with a thin residual layer on the bottom. To meet this demand, the molding temperature is increased until the polymer reaches a viscous state [20–22] with good flowability. Meanwhile, a metal frame is used to prevent the polymer from flowing away [20]. In this paper, they were heated up to 190 °C, which is 80–90 °C above the T_g of PMMA. Then the molding force of 30 kN is applied on a 10 × 10 cm² area for 10 min. After a blind hole with a thin residual layer was formed, the pins were continuously pressed into the buffer layer as an indentation with a depth greater than the thickness of the residual layer, which is described in section 2.5. The molding force was released after they were cooled down below 85 °C. The overall hot embossing parameters are shown in table 1.

2.5. Micro-indentation process

The indentation is utilized to remove the polymer residual layer by pins and sidewall of indents during the hot embossing process. After the blind hole was formed, the pins and thin residual layer were pressed into the buffer layer at molding temperature. The depth of indents is kept greater than the thickness of the residual layer. Then the edges of the residual layer can be cut by tough squeeze and friction between pins and sidewall of indents. In this paper, the depth of indents is determined by indentation force and time. The force applied on the mold insert was transferred to pins as the indentation force with some loss due to hydrostatic pressure inside the viscous polymer. The indentation process is optimized by evaluating on the indent depth dependent on molding force and time. The indentation process parameters are the same as those in the previous molding process, as shown in table 1.

3. Results and discussion

3.1. Results

A polymer via hole array on a millimeter scale and microscale was fabricated by a combination of hot embossing and indentation processes. A square via hole array of 1.0 mm side length is shown in figure 2. All the 11 × 11 square holes on a

10 cm × 10 cm area were opened. The white square array on buffer layer indicates that the polymer residual layer adhered to the buffer layer, as shown in figure 2. Regarding topography at micro scale, the edge of the through holes is clear and trim except for some defects. The polymer micro hole array of 100 μm diameter is shown in figure 3. The thickness of polymer samples shown in figure 3 is less than the pin height of 50 μm. The main reason is that the pins were pressed into the buffer layer with a depth up to tens of μm. Then the final thickness of the embossed polymer sample is equal to the height of pins minus the depth of indentation. Thus the actual thickness of the embossed sample is less than 50 μm. The edges of the through holes are clear and trim too, but there are no obvious defects. This indicates that our fabrication process has the ability to open even smaller via holes.

3.2. Discussion

3.2.1. Thickness of residual layer. The optimized thickness of the residual layer is critical both for hot embossing and indentation processes. A thinner residual layer is highly desired to reduce the indentation requirements such as depth of indents. However, this will increase hot embossing requirements including molding temperature, force and time. Here we first investigated the reduced thickness of the residual layer dependent on the hot embossing process. The final thickness of the embossed area drops quickly with molding temperature since the mechanical strength of the polymer reduces with temperature [22], as shown in figure 4. The molding temperature of 190 °C was selected to avoid entrapped bubbles inside the polymer when temperature is too high. In order to measure the thickness of the residual layer defined by pins, a hard stainless steel blank plate was used to support the polymer sheet. The residual layer adhered to the stainless steel plate with no indentation. The process parameters are shown in table 1. The thickness was directly measured by the stylus profiler P16 (KLA-Tencor, USA). The thickness of the residual layer varies from 4 to 32 μm. It was caused by the non-uniform contact between the mold insert and the metal plate. This can be improved by flatness adaptation with hydrostatic pressure by the confined viscous polymer, which is described in section 3.2.4.

3.2.2. Topography of indent on Al buffer layer. Topography of indentation heavily affects the opening via hole process. This demands new aspects in addition to the conventional indentation process [23–25]: (1) the sidewall of indents is almost vertical; (2) there is no obvious sinking in or pile up on top edges [23–25]; (3) the depth of the indents array is uniform, and can be controlled larger than the thickness of the residual layer.

Al alloy 1100 was used as a buffer layer for its good deformability and much lower hardness than nickel or stainless steel. The microscopic and SEM images of indents of 400 μm diameter are shown in figure 5. The residual polymer film on the indentation bottom was removed by acetone. The profile of the indent is shown in figure 6. The bottom line of the profile denotes the bottom surface of the indent. The boundary of the

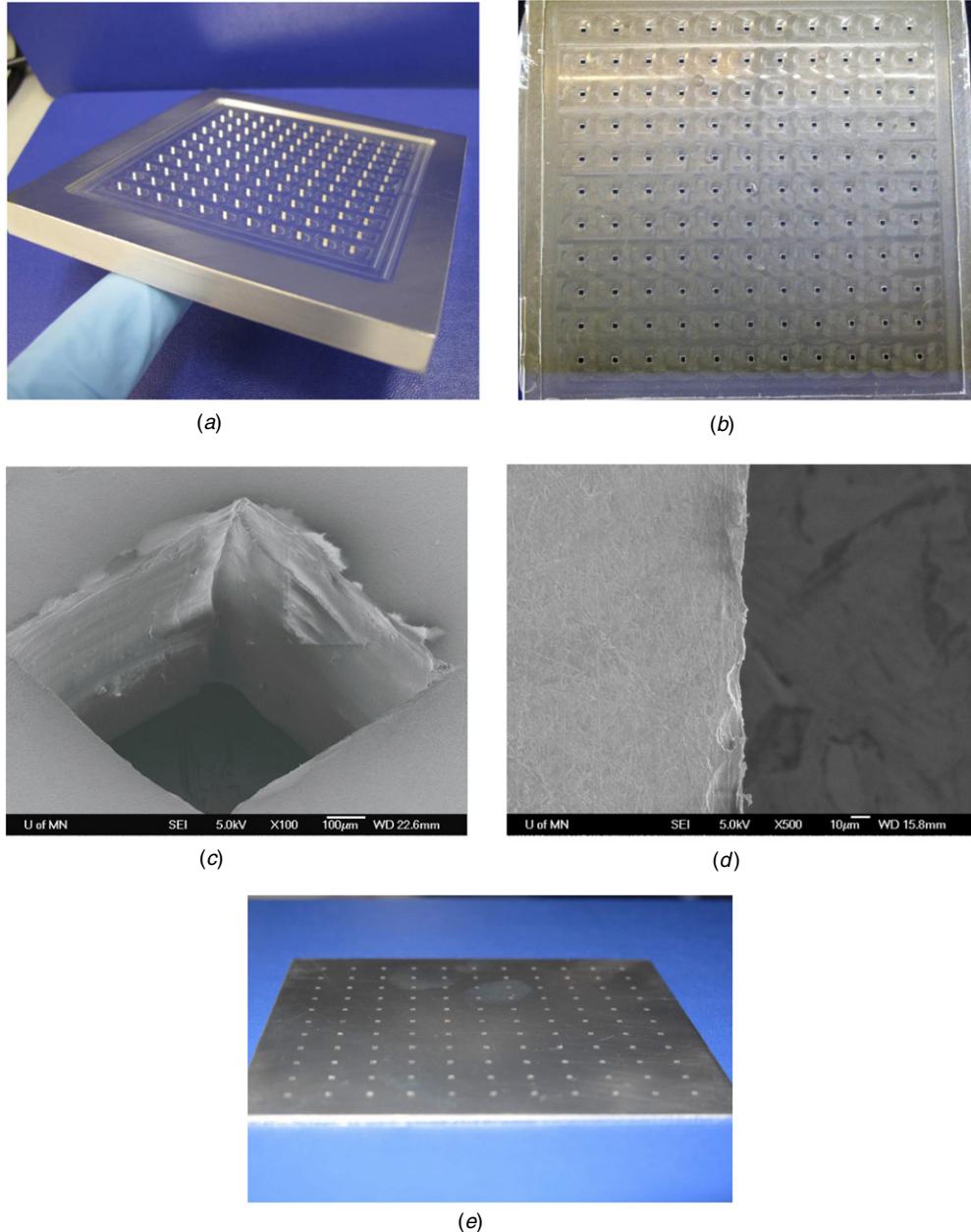


Figure 2. Hot embossed square via hole on a millimeter scale. (a) CNC machined mold insert with a 11×11 array of square pins; (b) opened 11×11 square via holes with a side length of 1.0 mm and a depth of 1.0 mm; (c) SEM image of a square hole shown in (b); (d) SEM image of a via hole edge shown in (c); (e) white squares on the metal buffer layer are the polymer residual layer.

indentation is clear, and the sidewall is close to vertical. This feature promises tough contact between sidewalls of pins and indent. In this manner, a polymer residual layer can be cut by a shearing process. No obvious sinking in or pile up was found on the edges. This ends in a flat embossed via hole as shown in figure 3. The drape on the sidewall can also tear the polymer squeeze flow.

The uniformity of the indent depth was also affected by the contact between the pins and buffer layer. Some small depth of indents, from 2.5 to $12 \mu\text{m}$, was caused by loose contact between pins and buffer layer, as shown in figure 6. It was improved through flatness adaptation with hydrostatic pressure by the confined viscous polymer, which is described in section 3.2.4.

3.2.3. Open via holes by indentation. The indentation process opens the via hole through two possible mechanisms: (1) the edge of the polymer residual layer was torn by tight contact and shearing movement between pins and sidewall of indents; (2) adhesion force assisted the residual layer to stick to the bottom of indents.

Polymer via holes on a millimeter scale and microscale were successfully opened by pins and vertical sidewalls of indents with no sinking in or pile up, as shown in figure 5. As a comparison, the indentation process by the round tip indenter was investigated, as shown in figure 8. The depth of indents varies from 4 to $38 \mu\text{m}$. However, all these via holes were not completely opened although the maximum depth of indents is much greater than the thickness of the residual

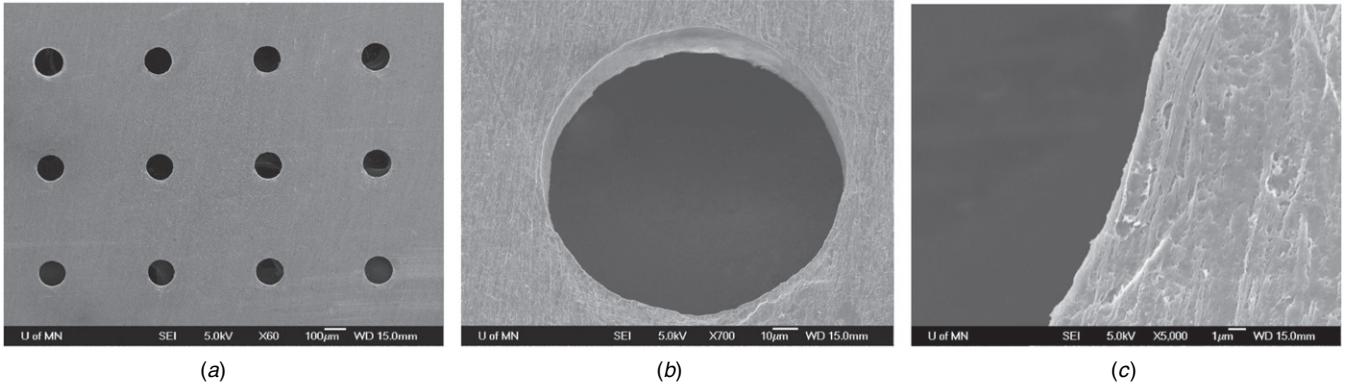


Figure 3. SEM image of a hot embossed micro via hole of $100\ \mu\text{m}$ diameter. (a) Rear side of the opened up via hole array with the removed residual layer; (b) zoomed via hole shown in (a); (c) zoomed via hole edge shown in (b).

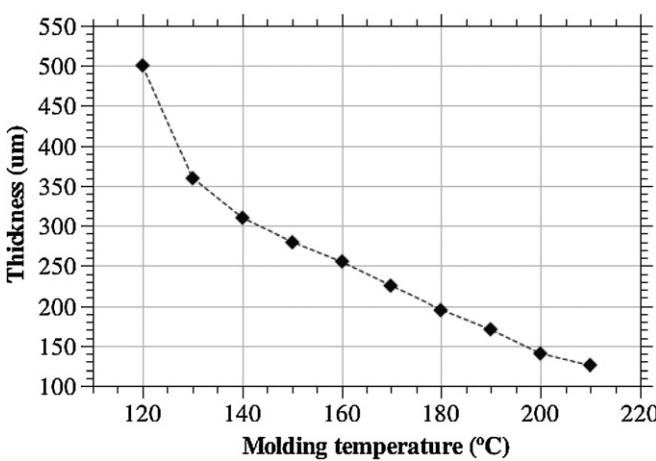


Figure 4. The thickness of hot embossed blank polymer film depends on molding temperature. The molding force of 30 kN was applied on blank mold insert for a duration of 300 s, the original size of PMMA is $5 \times 5\ \text{cm}^2$ with $500\ \mu\text{m}$ thickness.

layer. This is because that pile up profile cannot provide a strong enough shearing process between pins and sidewall of indents. By comparing these two different indentation processes, we believe that the flat indenter is better to generate vertical sidewalls to open via holes. In fact, the mold inserts by the CNC machining process and the UV-LIGA process have flat top surface and almost vertical sidewall. This will contribute to the first mechanism.

Adhesion force also assists the opening process. The roughness of buffer layer may enhance the adhesion force and cause the residual layer to tear strongly and stick to the bottom of indents, as shown in figure 7.

3.2.4. Flatness adaptation by hydrostatic pressure from a confined viscous polymer. A poor uniformity of contact between pins and buffer layer causes a low ratio of opened via holes due to the mismatched residual layer thickness and the depth of indents, as shown in figure 9. Possible reasons for this poor uniformity include (1) parallelism of hot platens

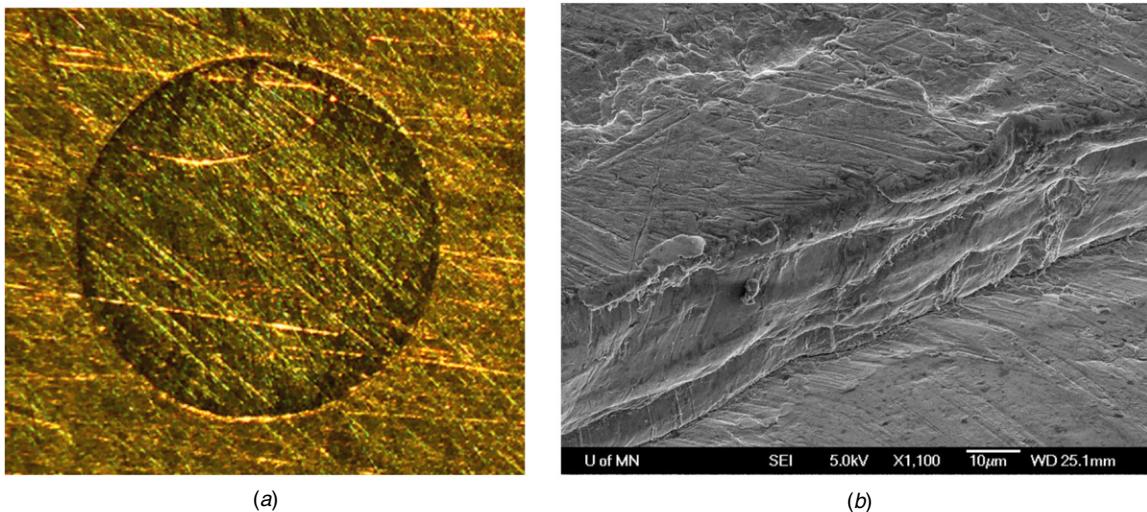


Figure 5. Topography of the indent on an Al buffer layer. The residual polymer film on the bottom of the indent was removed by a solvent. (a) Microscopic CCD image of the indent with a diameter of $400\ \mu\text{m}$; (b) SEM image of the sidewall of the indent in (a), the depth of the indent is larger than $20\ \mu\text{m}$.

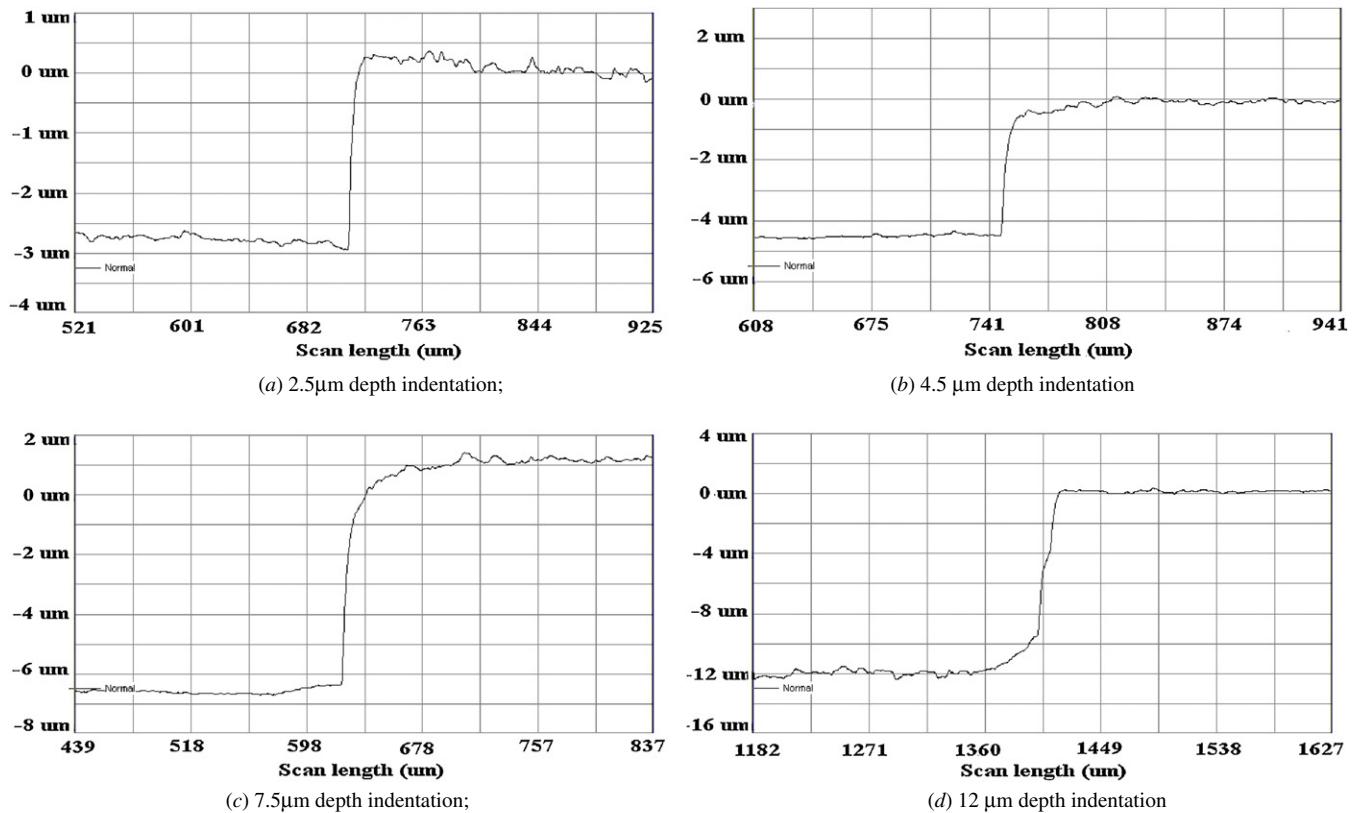


Figure 6. Some small depth of indents caused by loose contact between the pins and buffer layer. The measured four small thicknesses were randomly selected on the 4×4 inch area. The residual polymer film on the bottom of the indentation was removed by a solvent. (a) $2.5 \mu\text{m}$ depth indentation; (b) $4.5 \mu\text{m}$ depth indentation. (c) $7.5 \mu\text{m}$ depth indentation; (d) $12 \mu\text{m}$ depth indentation

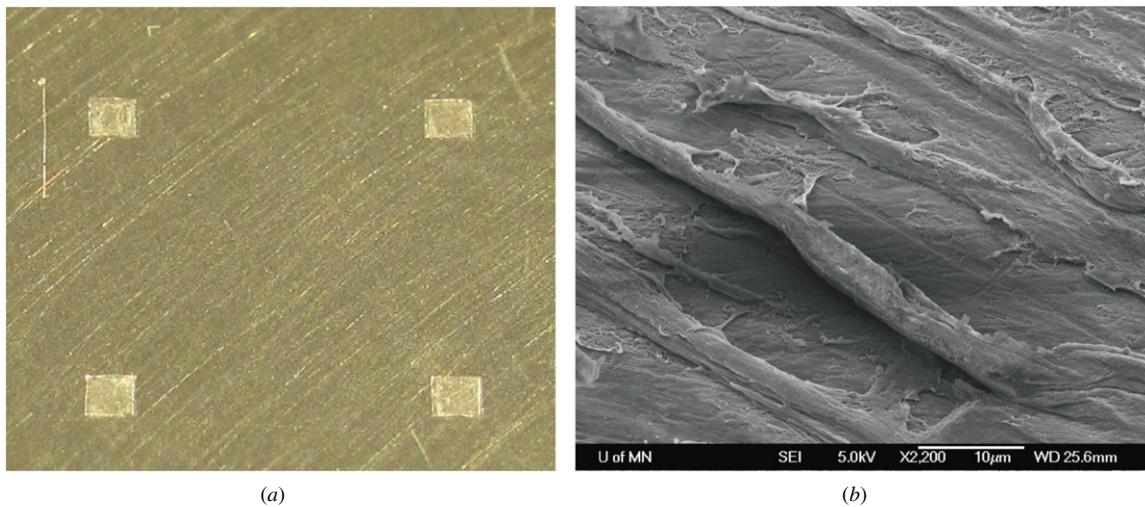


Figure 7. Polymer residual layer sticks to the bottom of the indent on the buffer layer: (a) microscope CCD image of indentation containing a polymer residual layer in a $1 \times 1 \text{ mm}^2$ square. (b) SEM image of a very torn polymer residual layer in (a).

in the embossing machine; (2) flatness of the mold insert; (3) thickness uniformity of the metal buffer layer. For example, the UV-LIGA nickel mold insert may bend due to inner stress during the electroforming process. In our case, the depth of indentation is only around a few tens of microns. So even a few microns displacement on flatness of the mold insert may cause via holes not to be opened.

In this paper, the uniformity of contact between pins and buffer layer was improved by flatness adaptation using

hydrostatic pressure from the confined viscous polymer, as shown in figure 10. In addition to previous process setups, another confined polymer with higher T_g was placed beneath the metal buffer layer. This polymer becomes viscous with high hydrostatic pressure during the molding process and causes the buffer layer to deform to adapt to the mold insert. Meanwhile, a uniform force load was transferred to pins. We investigated hot embossing of 384 holes with a diameter of 100 μm on a 6 inch area. Only 230 holes were opened with

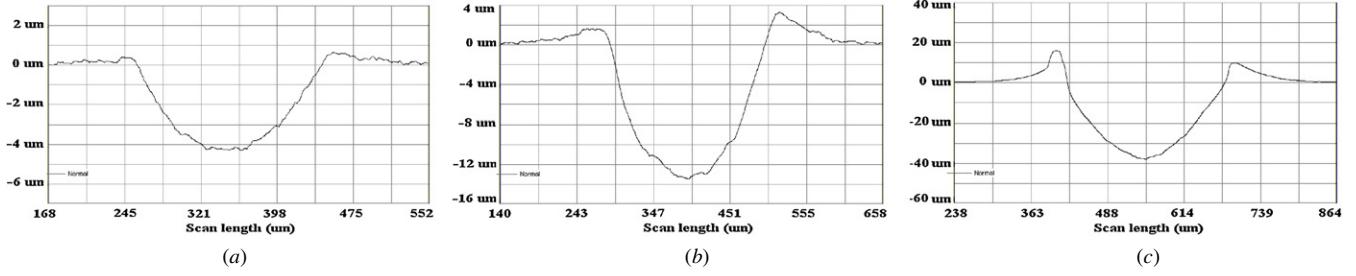


Figure 8. Pile up on the indent by a round indenter. (a)–(c) Indent with a depth of 4.2, 13 and 38 μm , respectively.

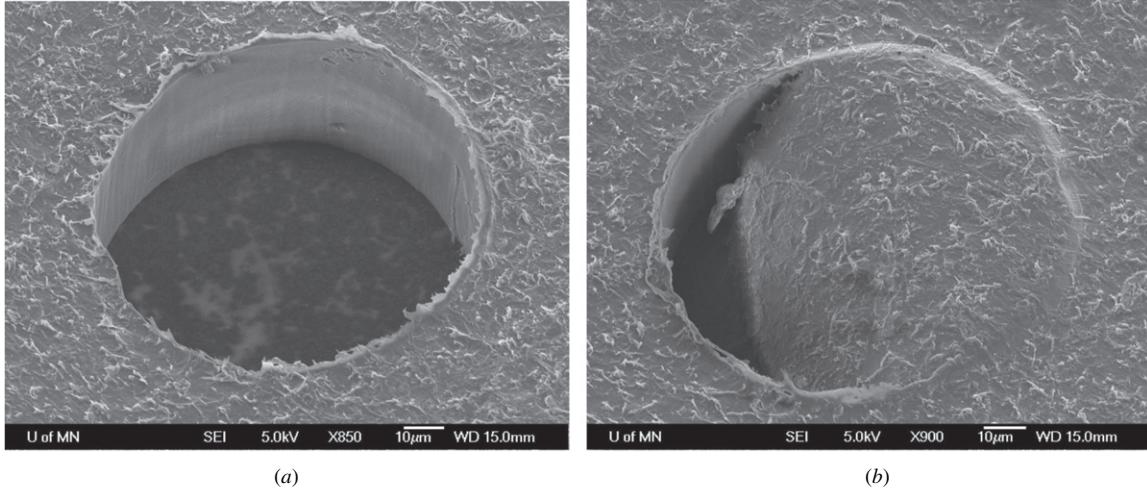


Figure 9. Unopened via holes caused by non-uniform contact between the pins and buffer layer. (a) Opened via hole; (b) unopened via hole.

no flatness adaptation. In order to improve the ratio of opened holes, hydrostatic pressure by the confined viscous polymer is used to obtain uniform force load on pins. In this way, 378 holes on a large area were opened.

3.2.5. Lifetime of the mold insert. Lifetime is another important aspect to the mold insert in our developed process. The metal buffer layer does tend to attack the mold insert in our case. The lifetime of the mold insert is much less than that in the normal hot embossing process. There are several possible reasons for this change. Firstly, the hardness of the mold insert and the buffer layer play important roles. In our case, the hardness of the metal buffer layer is much higher than that of the soft polymer, and cannot be neglected when it is compared to that of the mold insert. For example, the Al buffer layer has a hardness of Brinell 23, while nickel has a normal hardness of Brinell 90 to 140 [17]. This mismatched hardness of materials only promises no more than 30 cycles for hot embossing and indentation processes. Then the pins collapse. Secondly, the uniformity of contact between pins and buffer layer is also very important. Poor uniformity of contact causes force over load on part of the pins, and reduces the lifetime of the mold insert. In this case, we found that the curly mold insert can only be used ten times before part of the pins collapse. Thirdly, the indentation force also affects the lifetime of the mold insert. Our experiment results show that the collapse of pins accelerates when the indentation force was increased from 30 to 50 kN.

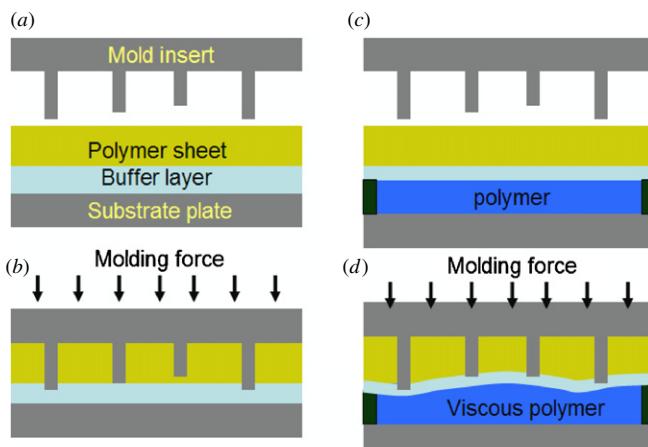


Figure 10. Sketch of flatness adaptation by hydrostatic pressure from a confined viscous polymer. (a) and (b) Only parts of pins were pressed into the buffer layer due to the poor flatness of the mold insert. (c) and (d) Metal buffer layer deforms in response to hydrostatic pressure from a confined viscous polymer and more holes were opened.

3.2.6. Polymer properties on indentation process. Polymer properties are also important in the indentation process. In this work, we demonstrated hot embossing of the via hole

using different polymers including PMMA and PP. PMMA and PP are typical amorphous and semi-crystalline polymers, respectively. They have different indentation performances in our case. For example, a PMMA residual layer can be completely cut on a shallow indent with a depth less than 10 μm . PP needs a deep indent with a depth more than 10 μm . The possible reason is that PMMA thin film is fragile, while PP thin film has good malleability and can withstand tough squeeze during the indentation process. Anyway, it is still possible to use other polymers in our developed fabrication process since their strength is much lower than that of the metal buffer layer.

4. Conclusion

A new fabrication approach for a polymer micro via hole array on a large area is presented by a combination of indentation and hot embossing processes. Compared with conventional hot embossing, only an additional Al alloy buffer layer is used to support the polymer sheet, and acts as an indentation receptor for pins on a mold insert. There are two stages of the fabrication process: (1) mold blind holes with a thin residual layer through hot embossing; (2) press pins and residual layer through the metal buffer layer as an indentation with a depth larger than the thickness of the residual layer. During the second stage, the edge of residual layer was cut by the pins and sidewall of indents. Polymer via holes at millimeter scale and microscale were successfully opened. A via hole array on a large area was also opened by improving the uniformity of contact between pins and the buffer layer through flatness adaptation with hydrostatic pressure from a confined viscous polymer. These experimental results indicate that our developed process promises a low-cost mass fabrication of polymer micro via arrays on a large area substrate. This method compares well with the conventional hot embossing process, and there is no alignment operation needed. In the future, we will focus on improving lifetime of mold inserts and fabricating smaller via holes using this new approach.

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