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TECHNICAL NOTE

Rapid patterning of slurry-like elastomer composites using a laser-cut tape

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Abstract

We present a cleanroom-free, simple and low-cost fabrication approach utilizing a laser-cut tape for rapidly patterning slurry-like elastomer composites. A conductive polydimethylsiloxane (PDMS) composite was chosen for demonstration in this paper due to its wide use of sensing and heating in many applications. Two fabrication schemes were developed: embedding in a PDMS matrix and relieving on a PDMS substrate. In both schemes, the patterns were first inscribed on adhesive tape using a CO₂ laser. The patterned tape then served as a positive mask when spreading the conductive PDMS over it. The patterns were eventually transferred to a substrate after scraping the excessive composite with a razor blade and then removing the tape. The feature resolution of the technique was about 90–100 μm primarily determined by the laser beam diameter, the translational speed and the power. The height of the patterned structures was associated with the thickness of the tape, which ranged from 76.1 ± 4.3 μm to 168.9 ± 8.2 μm in this study. A thicker structure can be achieved by stacking more adhesive tapes. For a practical demonstration, the conductive PDMS was patterned on a PDMS substrate serving as a heating element. The elastomeric microheater was successfully heated to 92 °C with a power of 210 ± 12 mW applied.

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

1. Introduction

An elastomer can be given a new function by mixing it with a filler. The elastomer composite is not only endowed with a new capability but also highly compatible with the original material. Currently, polydimethylsiloxane (PDMS) is the most common elastomer used for various fillers. Some researchers have attempted to use carbon blacks [1, 2], carbon nanotubes (CNTs) [3] and metallic powders [4] to make a conductive PDMS composite for sensing and heating. In addition, paraffin, a wax able to change volume as its phase changes, is widely used for generating a large force and a stroke at the microscale level. A PDMS/paraffin composite thus provides repeatable movement for a thermally actuated pump [5, 6]. A PDMS composite can be very viscous and sometimes slurry-like, causing a difficulty in spin-coating or patterning using conventional photolithography. Several techniques regarding

PDMS patterning were reported. A photopatternable silicone elastomer [7, 8] was realized by introducing an appropriate photoinitiator into a PDMS prepolymer. Despite many advantages due to photolithography, the polymerization cannot be activated if the material is opaque. Ryu *et al* [9] devised a method using a razor blade and a photoresist to precisely pattern the silicone elastomer for various applications. Depending on the quality of the photoresist, the claimed minimum thickness was 2 μm after polishing. In the same fashion, Niu *et al* [10] performed conducting composites on a substrate. The surface must be again polished to remove the residual films around the edges before developing. However, this final step may sometimes damage the microstructures. An alternative utilizing a cutting plotter named Xurography was firstly introduced by Bartholomeusz *et al* in 2005 [11] to make micromolds for PDMS molding. Positive features down to

35 μm and negative features down to 18 μm were achieved with a 25 μm thick tape. However, overcutting occurred at the start and the end spots of patterns due to the blade angle and the cutting mode. More recently, Kim *et al* [12] demonstrated microfluidic systems using a PDMS/polymer tape composite. The PDMS was spin-coated on a double adhesive tape and the composite was then patterned by a knife plotter. The completed composite with patterns can be bonded to various materials without further processing. However, this method is not suitable for most PDMS composites due to their high viscosity.

To deal with a PDMS composite, a robust fabrication method should be involved. Luo *et al* [13] attempted to replace the conventional microfabricated mold with a laser-patterned tape. According to their studies, the laser line width on a tape was a function of the laser power and the laser translational speed. The laser line depth was also associated with the laser translational speed. Taking all the factors into consideration, a reliably produced feature size was 200 μm . We produced a positive tape mask in the same manner. By sticking the tape mask on a substrate and applying the PDMS composite over it, the designed patterns can be rapidly transferred after peeling off the tape. It should be noted that a laser source is preferred since a cutting plotter always ends up with overcutting, causing smears around the edges of the patterns.

Two fabrication schemes were developed in this paper: (1) patterns above the surface of a PDMS substrate (relief patterns) and (2) patterns below the surface of a PDMS substrate (embedded patterns). A conductive PDMS composite containing PDMS and metallic powder was employed for the demonstration. Both schemes have different purposes in applications. For instance, the relief patterns can be used for a chemical sensor to capture the target molecules in the ambient environment [14]; the embedded patterns can be used for an inner sensor or an electrode in a microchip [15]. For a single-layer tape, the minimum resolution of the pattern was around 90–100 μm . By stacking three adhesive tapes, the thickness was increased from $76.1 \pm 4.3 \mu\text{m}$ to $143.7 \pm 11.6 \mu\text{m}$ for a narrow strip of 0.4 mm in width and $87.0 \pm 2.3 \mu\text{m}$ to $168.9 \pm 8.2 \mu\text{m}$ for a broad strip of 1 mm in width. Eventually, a flexible microheater was fabricated with a relief pattern using the developed scheme. The microheater was successfully heated to 92 °C with a power consumption of $210 \pm 12 \text{ mW}$. The demonstration implies the feasibility of the current fabrication technique in practical applications.

2. Experimental details

In this paper, an adhesive tape (Scotch[®] 810 Magic[™], 3M) was used to act as a positive mask. The nominal thickness of each adhesive tape was 56 μm (2 mil). The cutting tool was a CO₂ laser (Professional Series, Universal Laser Systems Inc.) with the maximum power up to 150 W and the peak wavelength centered at 10.6 μm . The tape was placed on a temporary PDMS substrate and sent to the laser system for rapid patterning. Only 7% of the maximum power was required to cut a single-layer tape. The power was increased to 10% as the number of tapes went up to 3. An upright

microscope (Eclipse ME600, Nikon Corp.) with a $4\times/\text{NA} = 0.1$ objective lens was employed to measure the patterns and their dimensions.

Two fabrication schemes were developed with laser-cut tapes. The first scheme aims to make relief patterns by applying a PDMS composite on the surface of a PDMS substrate. The second scheme aims to make embedded patterns by burying a PDMS composite inside a PDMS substrate. To facilitate the study, a conductive PDMS composite, a mixture of PDMS and metallic powder, was chosen as a representative of the highly viscous elastomer composites in this case. Characterizations and preparations of such a material were discussed in the relative papers [4, 16]. The schematic of the fabrication procedures is illustrated in figure 1. Both the relief and the embedded patterns require a laser-cut tape to transfer designed patterns. The tape is prepared by the CO₂ laser for a positive mask. The patterns are applied to a substrate by spreading the conductive PDMS composite over the tape. To ensure a desired thickness, the excessive composite is removed by scraping the surface with a razor blade. The final patterns will then take shape after removing the tape. For a relief pattern, the rest of the work is simply curing the 'wet' composite in a convective oven at 80 °C for 30 min. However, for an embedded pattern, more steps need to be done before it can be used. After the composite is fully cured, a PDMS prepolymer is poured onto the composite to submerge the patterns. This way the PDMS composite and its surrounding PDMS will form strong bonding to each other, making the pattern nicely embedded in the PDMS matrix. The substrate containing the PDMS prepolymer is cured at 80 °C for an hour. An embedded pattern is then accomplished as the bulky PDMS is peeled off. It should be noted that the substrate for this scheme must be a rigid wafer (e.g. a Si wafer or a glass wafer) to support the fabrication. Furthermore, a thin film of Teflon (0.5% AF2400, DuPont) added on the substrate before applying the conductive PDMS composite is recommended in order to prevent sticking. Unlike the relief structures, the embedded structures show a flat surface due to its upside-down configuration. This feature significantly reduces the difficulty in bonding with other components.

3. Results and discussion

Figure 2 shows the test patterns inscribed on a tape using the laser system. The minimum feature resolution is about 92 μm and is likely to vary between 90 μm and 100 μm depending on the laser power and translational speed. The conductive PDMS patterns transferred from the single-layer tape are shown in figure 3. The patterns are eventually relieved on a PDMS substrate. Four closeups of the patterns are further depicted at the bottom of the figure. The images disclose some features of using this technique: (1) the fabricated circles have a good agreement with the original layout in both dimension and geometry. (2) The four corners of each square are rounded off due to the laser beam diameter. Since the laser beam diameter is fixed, the round-off effect will be more significant as the geometry size reduces, which deforms the pattern seriously.

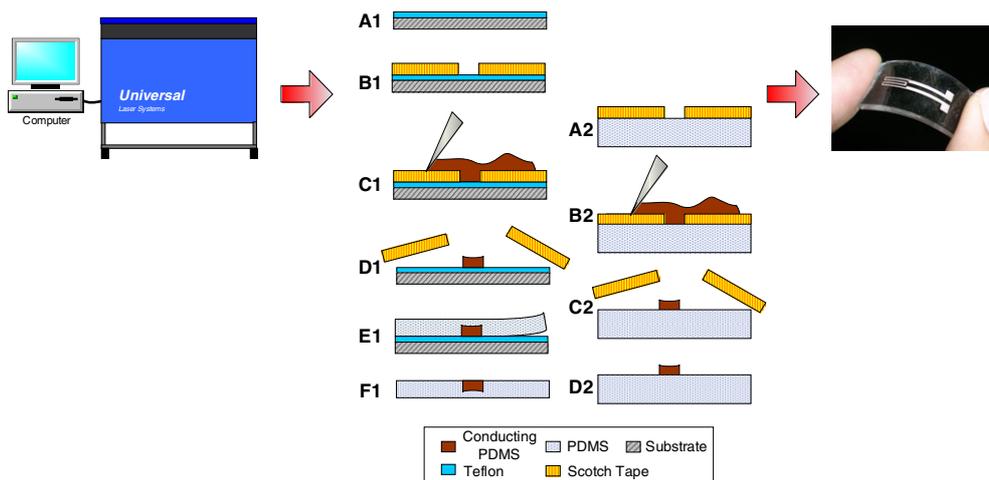


Figure 1. The schematic of the fabrication flow charts for a relief pattern (A1–F1) and an embedded pattern (A2–D2). (A1) The surface is pre-processed with Teflon. (B1) A laser-cut tape is placed on a substrate. (C1) Apply the conductive PDMS composite over the tape and then remove the excess with a razor blade. (D1) Peel off the tape and cure. (E1) Pour PDMS, cure and then peel off. (F1) An embedded pattern is obtained. (A2), (B2) and (C2) are the same as (B1), (C1) and (D1), respectively. (D2) A relief pattern is obtained. The upper-right photo shows a microheater (a relief pattern) produced by the developed fabrication technique.

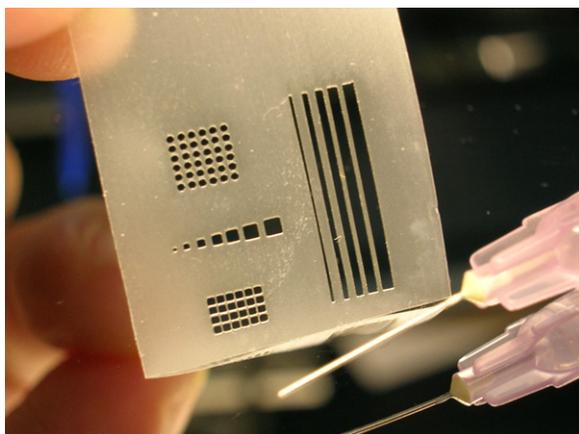


Figure 2. The test patterns on a laser-cut tape.

(3) For long strips, the slightly ragged edge may occur due to the defect of the laser cutting on a tape.

The cross-sectional profiles of the relief and embedded patterns were investigated and the results are shown in figure 4. Figures 4(A) and (C) exhibit the case of relief patterns, in which all of the circles were fabricated on the surface of the substrate. The cross-sectional profiles tend to be more curve-like when the patterns sit on an elastomer, such as PDMS. The cause of the curved profile is induced from the downward deformation of the elastomeric substrate when a force is applied on the top of the conductive PDMS (i.e. scraping excessive PDMS prepolymer with a razor blade). After the force is released, the elastomer recovers its shape and brings the over-filled conductive PDMS upward, resulting in the curved surface. In contrast, figures 4(B) and (D) show the case of embedded patterns, in which all of the circles were immersed in the PDMS matrix. The cross-sectional profiles of such patterns feature a flat surface, thus facilitating the bonding between the structures and the surrounding PDMS.

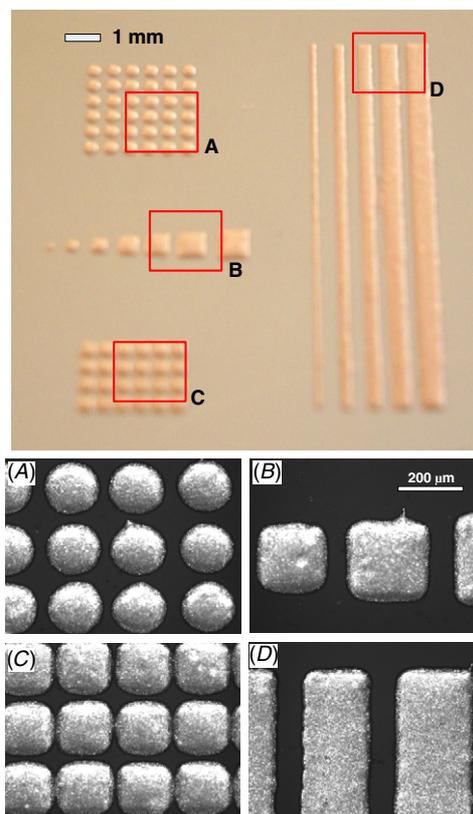


Figure 3. Images of the fabricated patterns. The red rectangles indicate the closeups of the patterns. (A)–(D) are some closeups of the selected regions. (A) A fraction of the 6×6 circle array; (B) two of a series of gradient squares varying from $140 \mu\text{m}$ to $520 \mu\text{m}$ in size (left to right); (C) a fraction of the 4×6 square array; (D) the tips of the long strips.

The thickness of the conductive PDMS was increased by simply stacking multiple adhesive tapes. The measured thickness was defined as the maximum height of the cross-sectional profile. The relationship between the thickness of

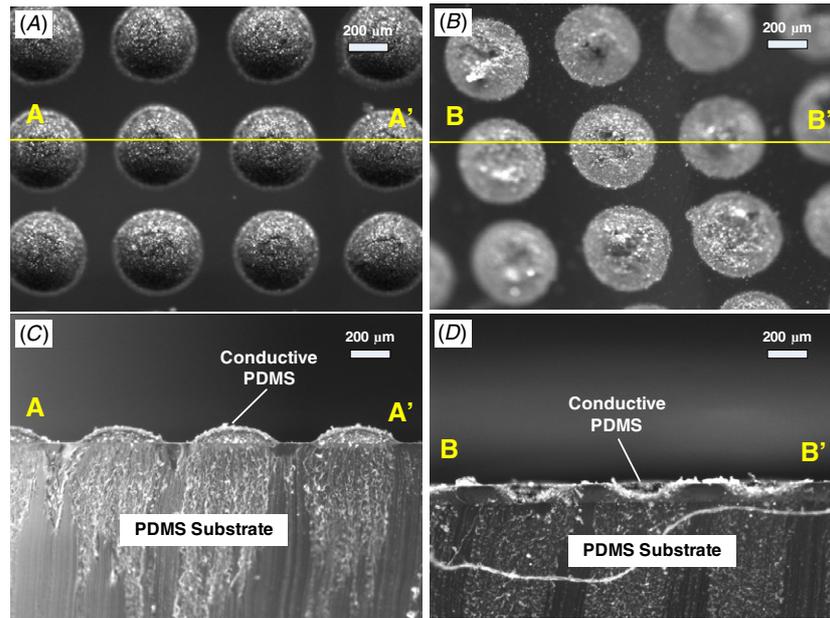


Figure 4. Micrographs of (A) the relief patterns and (B) the embedded patterns. All of the patterns were made with a single-layer tape. The cross-sectional profiles of the relief and embedded patterns are shown in (C) and (D), respectively. The average thickness is $93.5 \mu\text{m}$ for the relief patterns and is $90.3 \mu\text{m}$ for the embedded patterns.

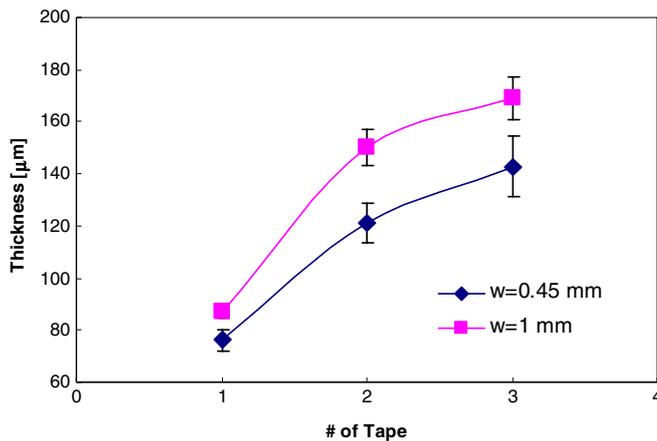


Figure 5. The relationship between the thickness of the patterned structures and the number of adhesive tapes.

the fabricated conductive PDMS and the number of adhesive tapes is shown in figure 5. For the pattern with a width of 0.45 mm , the initial thickness was $76.1 \pm 4.3 \mu\text{m}$ and became $143.7 \pm 11.6 \mu\text{m}$ when the number of tapes was 3. In contrast, the initial thickness and final thickness turned out to be $87.0 \pm 2.3 \mu\text{m}$ and $168.9 \pm 8.2 \mu\text{m}$ respectively when the width of the pattern was expanded to 1 mm . It was found that the thickness difference between the above two patterns primarily resulted from the same factor which caused the curved profile. The broad pattern allows one to fill in more conductive PDMS (i.e. more deformation in the substrate), while the narrow one does not. Moreover, part of the conductive PDMS may be removed with a peeled tape when the tape mask is too narrow and thick. This drawback causes the potential reduction in thickness for both cases when the number of tapes goes up, leading to the nonlinear relationship between the thickness and the number of tapes. Considering the fidelity of the transferred patterns,

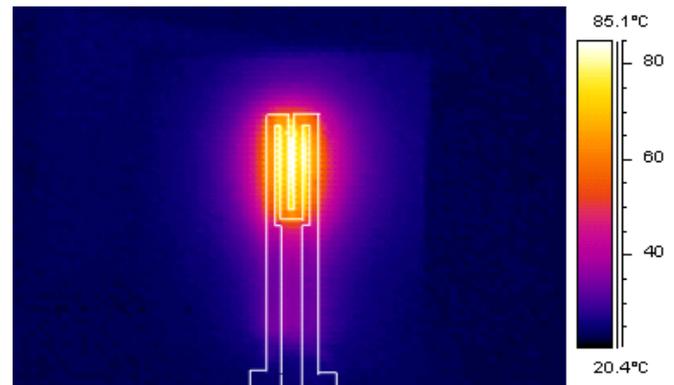


Figure 6. IR image of a conductive PDMS-based microheater fabricated by the rapid patterning technique using a laser-cut tape.

an ideal thickness of the stacked tapes should be maintained below $168 \mu\text{m}$ ($<6.6 \text{ mil}$) when the minimum line width is less than 1 mm .

For a feasibility evaluation, a microheater made of the conductive PDMS using the developed approach was demonstrated. The measured resistance at two electrode pads was 10.1Ω . The dimension of the heating wire was $300 \mu\text{m}$ in width and 29.2 mm in length. Joule heating was applied to the microheater operations. An IR image indicating the temperature distribution is depicted in figure 6. The result showed that only $210 \pm 12 \text{ mW}$ was needed for heating the wire to 92°C . The detailed characterizations of the microheater can be referred to the paper [16].

4. Conclusion

Currently various elastomer composites are being developed in a wide spectrum of applications as elastomers become more

prevailing materials in microfabrications. Commonly used composites, such as conductive PDMS or PDMS/paraffin composite, are highly viscous and slurry-like. Therefore, a robust patterning technique is essential in order to deal with such kind of materials.

In this paper, we present a rapid patterning technique with a laser-cut tape for viscous elastomer composites. Conductive PDMS was chosen for the demonstrations due to its popularity. To cover a wide variety of applications, two fabrication schemes, relief and embedded patternings, were developed. Limited to the current laser system, the minimum feature resolution of the patterns was only 90–100 μm . The thickness of the patterned structures can be adjusted by simply stacking adhesive tapes. However, the transferred patterns tend to lose their fidelity due to the damages from a peeled tape as the thickness is increased. An empirical thickness of the stacked tapes not more than 168 μm was recommended based on the current setup. A microheater fabricated by the developed approach was demonstrated for a feasibility evaluation. The microheater was successfully heated to 92 °C with a maximum power of 210 ± 12 mW applied. The demonstration implies that the rapid patterning technique is potentially suitable for more practical applications.

Acknowledgments

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