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LOW-COST AND RAPID FABRICATION OF MICROCHANNELS BY KIRIGAMI-BASED SOOT COATING FOR THE DETECTION OF EXPLOSIVES

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ABSTRACT

This paper presents a facile and low-cost fabrication method to construct microfluidic channels by means of a simple candle soot coating process. The fluid channels are defined via a shadow mask fabricated by a Kirigami cutting scheme and placed on top of a hydrophilic substrate. The candle-soot coating process is followed to convert the rest areas with the superhydrophobic property. High-resolution shadow masks can be built via the computer-aided design software. The resulting micro channels are found to have good inert chemical properties and remarkable durability for repeated usages. Three distinctive achievements have been accomplished in this work: 1) an ultra-fast process for the fabrication of microchannels on an area of 18 x 18 mm² of only ~120 seconds; 2) good lateral channel resolution of ~300 μm; and 3) demonstration of a practical application to detect multiple explosive ions such as NO₃⁻ and NO₂⁻ as well as pH values within ~90 seconds. As such, this low-cost, easy-to-fabricate method is a promising alternative to those of traditional microchannel fabrication techniques.

KEYWORDS

Micro Channel, Kirigami Cutting Scheme, Mass Fabrication, Superhydrophobic, Explosive Detection.

INTRODUCTION

Microchannels are fundamental components in a variety of devices for uses in chemical/biomedical engineering, microfluidics, and lab-on-a-chip systems [1-5]. One major advantage of microchannels is their ability to control the fluid flow at the microscale to enable experiments with great precision and repeatability. Additionally, the small sizes together with other miniaturized components could lead to significant cost savings due to both low material consumptions and low energy requirements than those used in traditional analytical systems. As a result, microchannels have played important roles in the development of modern systems, such as drug delivery [6,7], microreactors for chemical synthesis [8], and microscale sensors [9].

In general, the microchannel fabrication process is complex as it requires specialized processing technologies and intricate design flows. Presently, several methods have been commonly used to fabricate microchannels, including soft lithography, micro-milling, laser cutting, and 3D printing processes. The soft lithography process is suitable

for mass fabrication, but it requires specialized equipment and it could be time-consuming to make initial templates for duplications. The micro-milling process can sculpture arbitrary structures on glass or ceramic substrates with high precisions, but it is a serial fabrication process such that the production is restricted by the milling speed. Laser cutting and 3D printing techniques have been utilized to generate high customization and complex geometries but they all require relatively long periods of time to fabricate a simple microchannel [10,11].

In this study, an inexpensive, fast, and unconventional approach has been developed to fabricate microchannels that takes only about ~120 seconds to make microchannels in an area of 18 x 18 mm². In short, this method uses a Kirigami-based shadow mask [12,13] to define channels by

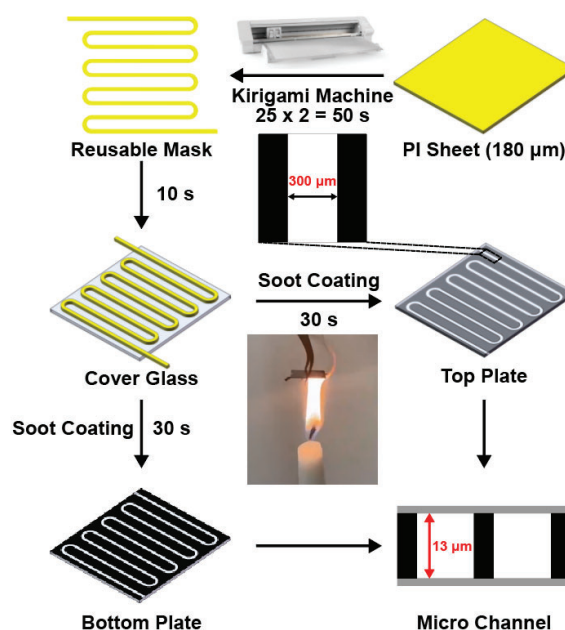


Figure 1: The overall fabrication process of the proposed superhydrophobic-hydrophilic surfaces for microchannels. The high-resolution shadow mask made of PI (Polyimide) is constructed by software-controlled cutting process and attached to the surface of a glass substrate. A 30-second carbon candle soot coating process is followed to modify the uncovered region to superhydrophobicity. After peeling off the reusable mask, superhydrophobic-hydrophilic patterns are created for structures such as microchannels.

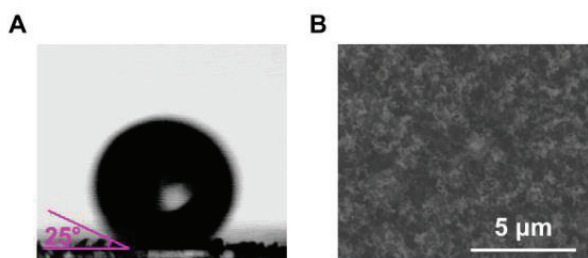


Figure 2: **A)** The optical photo of a water droplet on the superhydrophobic surface with a measured contact angle of 155° . This image is taken by the KRUSS DSA10-MK2 Drop Shape Analyzer System. **B)** The scanning electron microscopic (SEM) image of the candle soot coating layer on the glass substrate.

a superhydrophobic coating process by means of the candle-soot. High-resolution masks are created by cutting thin Polyimide films using a mechanical vinyl cutter controlled by a computer-aided design software. These shadow masks are then used as templates during the candle-soot coating process to deposit a thin carbon layer ($\sim 6.5 \mu\text{m}$) on the surface of a glass substrate, changing the surface property from hydrophilic to superhydrophobic as the liquid barrier. As a result, liquid such as water is confined to the hydrophilic channel region. The carbon layer is biocompatible, thermally stable, and chemically inert such that it is suitable for a wide range of sample manipulations and applications. For the proof-of-concept demonstration, three explosive ions have been detected simultaneously within 90 seconds, outperforming another paper-based device in a previous report with a detection time of about 5 minutes [14].

DESIGN AND FABRICATION

The proposed fabrication process is illustrated in Fig. 1. A $180\text{-}\mu\text{m}$ thick Polyimide (PI) film is utilized as a shadow mask material and a Silhouette Kirigami machine (CAMEO 3, Silhouette Inc.) is used to define and cut the designed microchannel patterns. This desktop commercial vinyl cutter is digitally controlled with a cutting blade to achieve a lateral resolution of $300 \mu\text{m}$. By selecting appropriate parameters such as cutting speed and depth, two PI shadow masks (for the top and bottom plates) with an area of $\sim 324 \text{mm}^2$ can be prepared within 50 seconds. To ensure the cutting quality, the PI film is attached on the top surface of the cutting mat and the resulting shadow mask can be used multiple times in the candle-soot coating process on top of an $18 \times 18 \text{mm}^2$ cover glass substrate. The candle-soot coating process takes only 30 seconds for each plate and the desired coating parameters can be adjusted by the wick dimensions, deposition time, and flame temperature [15]. After the deposition process, the mask is peeled off to expose the hydrophilic microchannel areas. By placing two processed cover glasses face-to-face together, the height of the microchannel is estimated at $13 \mu\text{m}$ due to the formation of the two soot layers from the top and bottom substrates. Overall, this fabrication process is fast of only ~ 120 seconds to enable quick customization of samples based on the Kirigami technique.

RESULTS AND DISCUSSIONS

The superhydrophobic property of the candle-soot surface has been characterized by the water contact angle measurement setup using a drop shape analyzer (KRUSS DSA10-MK2 Drop Shape Analyzer System). As shown in Fig. 2A, a contact angle of 155° is measured, indicating an ultra-hydrophobic surface as condensed water droplets are pulled to the top of the carbon nanostructures by a coalescent force as a result of the exceedingly small dimensions of these structures [16]. The scanning electron microscopy (SEM) image in Fig. 2B confirms the mesh-like surface after the candle-soot coating process on the cover glass.

The durability of the fabricated microchannels is tested by using a flushing droplet test as shown in Fig. 3A. Qualitatively, the most significant factor for durability is the superhydrophobic surface and the durability is defined as the number of droplets to change the surface property from superhydrophobic to hydrophilic. In this work, a syringe with a 0.5mm in diameter needle is used to sequentially release 0.5mL water droplets from a height of 2cm over the sample plate of the same point. The slope is set at a 20-degree angle and this angle is fine-tuned. If the angle is too large, the droplet can flush uncontrollably and if the angle is too small, the droplet may aggregate on the glass plate. Results shows the droplets could easily jump out of the plate due to the conservation of momentum. The superhydrophobic surface made of the candle-soot allows droplets to bounce quickly without residual water on the testing surface. The number of droplets required to remove the candle-soot coating layer is counted to characterize the durability. The destruction of the superhydrophobic surface can be clearly judged by the stationary water droplet on the surface or the adhesion of droplet on the surface without the jumping action. Once the droplet is no longer bouncing, the counting ends and the total number of droplets flushed is used for the durability characterization. A total of 30 sample plates have been fabricated and tested and the durability results are shown in Fig. 3B, with an average durability of 104 droplets. Even in the worst-case scenario, the surface could withstand 75 droplets, which is sufficient for most microfluidic applications.

The design strategy based on the Kirigami process offers great flexibility for processing a wide variety of

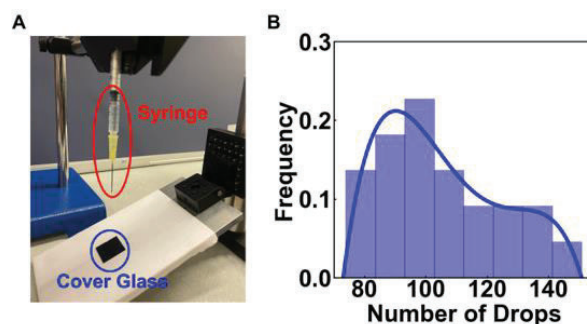


Figure 3: **A)** The experimental setup for the durability test. Droplets of 0.05mL are dispensed freely 2cm above the tilted surface with a slope of 20° . The durability is defined as the number of drops to destroy the super-hydrophobicity of the surface. **B)** Durability of the candle soot coating from 30 different samples.

microfluidic models (see Fig. 4). In this work, a novel fabrication method is proposed to allow easy customization with good lateral resolution of $\sim 300\ \mu\text{m}$ and the shadow mask template can be quickly modified. Fig. 4A depicts a binary tree pattern that can split the flow into multiple branches, making it particularly useful for droplet-based tests. Fig. 4B demonstrates a common pattern design that improves heat transfer performance in electronics by arranging long wandering paths in a limited region. In Fig. 4C, a compact spiral-shape flow geometry is shown to facilitate efficient fluidic mixing. Fig. 4D illustrates a precise lattice design that can be used as a filter or a separation device for particles or cells. Overall, this rapid fabrication method is promising for creating microchannels with high-resolution geometries for a wide range of microfluidic applications.

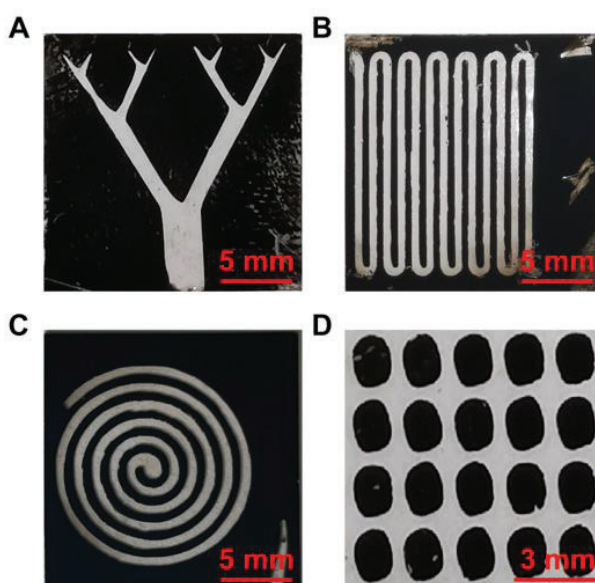


Figure 4: Several fabricated microstructures with good pattern resolutions, including: A) a binary-tree pattern for droplet splitting; B) the folded heat pipe pattern for the improvement of heat transfer; C) the compact spiral-shape pattern for efficient mixing; and D) the high-resolution lattice pattern for filtering and particle separation applications.

Using branch structures to divide liquid into finer parts and direct them to different locations is a common technique for manipulating fluidic flow in microchannels. Fig. 5 demonstrates a branch structure fabricated with the proposed method for the separation of liquid droplets into three parts. The whole plate has a dimension of 18 mm x 18 mm and contains microchannels with a width of 750 microns and a height of 13 microns (Fig. 5A). There are three branch channels, with a length of 9.9 mm, 7.4 mm and 9.9 mm respectively, originating from the starting point located at the center of the plate. Initially, the droplet is placed on the starting point of the bottom glass plate (Fig. 5A), which resembles a nearly spherical shape due to the superhydrophobic surface. The top glass plate is then aligned and assembled with the bottom plate. The droplet is directed to split into three parts and flow towards the three microchannels, driven by the pressure field that is

created by the surface tension force (Fig. 5B-5D). After 23 seconds, the liquid flows out of the three outlets, respectively (Fig. 5E). The dyed water droplet is successfully separated into three smaller droplets from the bulk liquid.

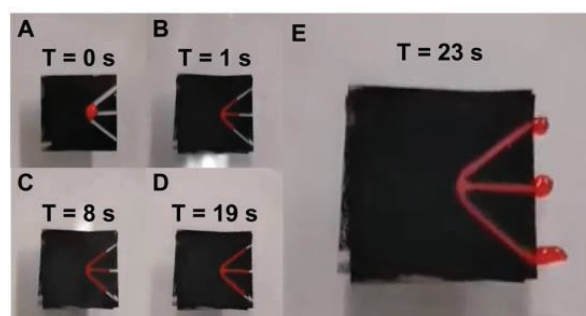


Figure 5: A)–E) A dyed water droplet flowing in the three-channel structure. The width of the channel is 750 μm , and the lengths of three channels are 9.9 mm, 7.4 mm and 9.9 mm, respectively.

By adding colorimetric papers as the explosive ion detectors as illustrated in Fig. 6, inorganic explosive ions such as NO_3^- and NO_2^- as well as pH values are tested at the three channels, respectively. The colorimetric paper used in the experiment is composed of a mixture of reagents that selectively react with the target explosive ions, resulting in a color change that is visible to the naked eye. The microfluidic device is made of the candle-soot carbon layer to form three parallel microchannels with a width of 750 microns and a height of 13 microns. The colorimetric papers are placed at the outlets of the microchannels, and the liquid samples are dropped on the starting point. The results for a testing liquid sample containing both ions with pH of 3 are shown in Fig. 6A, and results from a second liquid sample only containing NO_3^- with pH of 7 are shown in Fig. 6B. Only 60 s after the passage of the liquid to the colorimetric papers, the existence of the tested ions is clearly revealed. The total process for testing takes ~ 90 s, showing the rapid testing capacity of the detector. This experimental demonstration shows the promising potential in fast and low-cost detection of inorganic explosives.

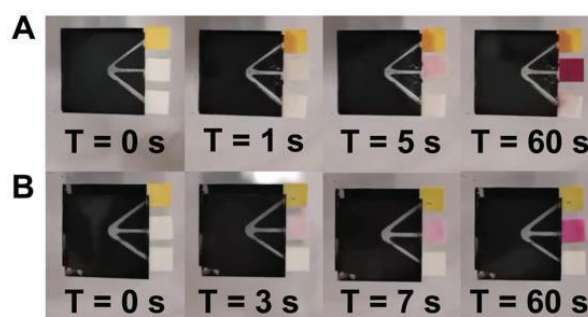


Figure 6: The experimental results for the explosive ion detections: A) a specimen containing NO_3^- and NO_2^- with pH level of 3, and B) a specimen containing NO_3^- and pH level of 7. The testing papers are for pH, NO_3^- and NO_2^- from top to bottom, respectively.

CONCLUSION

The fabrication of microchannels is complex and has limitations in terms of efficiency and design flexibility by using the conventional fabrication techniques. This paper reports a novel, fast, and low-cost fabrication method for microchannels. The new method utilizes hydrophilic and superhydrophobic areas on a plate to form microchannels, with the hydrophilic areas acting as channels and the superhydrophobic areas acting as liquid barriers. The microchannels fabricated using this method possess several outstanding attributes, including high customizability, good manufacturing precision up to about 300 μm in the lateral dimension, good durability for repeated shadow mask usages, and wide adaptability of the materials. Due to the high flexibility of the design scheme and the rapid manufacturing process, patterns suitable for a variety of applications can be processed and quickly optimized for testing microfluidic design parameters, including but not limited to droplet splitting detection, heat dissipation, and droplet mixing. Notably, the paper also provides an example of detecting multiple explosive ions within 90 seconds, resulting in cost saving and the potential for high-throughput testing.

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