MORPHOLOGY CONTROL OF MICROCHANNEL CROSS-SECTION USING SACRIFICIAL SPINNING FIBER

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ABSTRACT

This paper presents a novel method to manufacture specific cross-section microchannel by spinning profiled fiber. With spinning process, High Impact Polystyrene (HIPS) fibers with high profile degree can be drawn from a shaped spinneret orifice, and those fibers act as sacrificial mold to build microchannel with specific cross-section in PDMS. Microchannels with various shapes, from 55µm diameter circular to 220µm length square, from Y-shape, V-shape, L-shape to C-shape cross-section were both fabricated by the spinning-casting method. A PDMS swelling process has also been developed to remove large length-diameter ratio HIPS fiber (up to 1000:1) inside cured PDMS rapidly without mechanical extraction, it can also be used for rapid machining of complex three dimensional microchannels. This simple and mass productive method can improve specific surface area of microchannel, and provide various possibilities in microchannel design and fabrication.

INTRODUCTION

The shape of microchannel cross-section is important in microfluidic design. High profile degree microchannel can provide high contact area between liquid and channel, which is beneficial to many microfluidic devices and new compact thermal solutions [1]. Non-rectangular channels also have unique properties in inertial focusing which leads to various applications including microfluidic separation and enrichment of cells. The location and number of focusing positions had been analyzed with varying cross-sectional shapes and Reynolds number [2]. Several analytical studies for flow in noncircular channels are available in literature [3].

Many existing research works focus on morphology control of microchannel, anisotropy etching silicon process can generate rectangle and trapezoid cross-section microchannel; photoresist reflowing can build half round cross-section channel [4]; and curing hydrogel in shaped glass capillary can be used for circular, square and triangle cross-section microchannel fabrication [5]. Other complex cross-section micro channels with high profile degree, such as Y-shape and X-shape, are still challenging to obtain. Some methods, using Nylon stranded fiber and stainless wire as mold [6, 7], needs mechanical extraction to remove fiber, which may cause damage to channel surface. Therefore, a simple method for batch manufacturing of high profile degree microchannel is significantly needed.

In this paper, the goal is to develop a highly efficient method for the morphology control of microchannel by combining continuous manufacturing of profiled fibers in textile industry with PDMS casting processes. In traditional textile industry, shaped cross-section fibers can be made through shaped nozzle to produce textiles which show special luster or achieve ventilation function [8]. On the basis of this process, shaped PDMS microchannel can be obtained by using appropriate sacrificial materials as the fiber core in PDMS casting process. For this purpose, it is not only necessary to study materials which are suit for spinning and batch production, but also study reliable and rapid core removal methods.

EXPERIMENTAL METHODS

This spinning-casting process is based on spinning technology in textile industry, where shaped spinneret orifices are used to fabricate long and thin profiled chemical fibers. When melt polymer is injected into cold air through spinneret nozzle, the hardening spinning material inherits the shape of nozzle, and be drawn into long fiber at the same time. A similar process can be seen in 3D printing process where the melted material is extruded from a heated nozzle and hardened in a cooler environment to obtain the desired shape. After spinning, the cured profile fibers are casted into PDMS as sacrificial mold to build microchannel in PDMS (Fig.1).

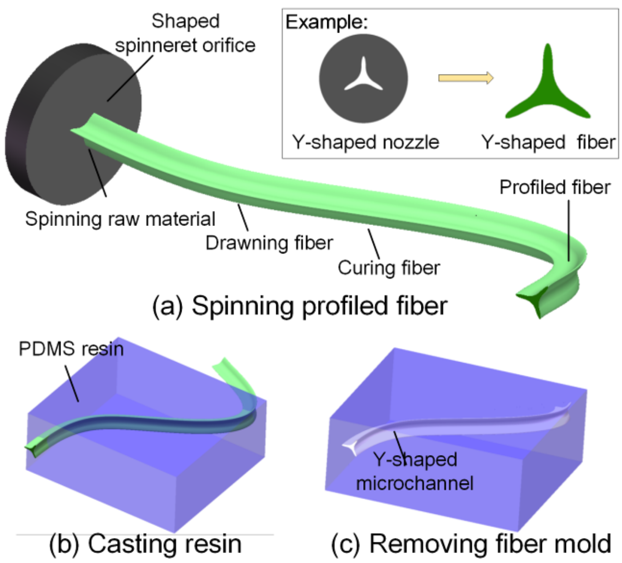

Figure.1 Fabrication process of specific cross-section microchannel by spinning profiled fiber as sacrificial mold.

In conventional spinning process, the softening point of the polymer and the viscosity characteristic are the most important characteristics. For microchannel applications in MEMS, since the fibers produced are intended to be used as sacrificial mold in PDMS casting process after spinning, other factors should also be considered. As some heavy metals and organic compound impurities in materials can lead to poisoning of the platinum catalyst in the PDMS mixture, the compatibility of raw materials should be paid attention to. The sacrificial material should be removed from the PDMS after curing, for this reason the solubility of the polymer material in common organic solvent is also important.

Common chemical fiber materials and 3D printing material, as well as some thermoplastic materials are both considered as spinning material, including polyethylene (PE), polystyrene(PS), polyvinyl chloride(PVC), nylon, polyethylene terephthalate(PET), polylactic acid(PLA), acrylonitrile butadiene styrene(ABS), hydrogenated rosin glyceride, Dama resin, and hydrogenated terpene resin. In those materials, small molecular resins like hydrogenated terpene resin are easy to be pulled out to long filament, but those low strength filaments are fragile because they do not have long-chain structure in polymer. Some plastics such as PE, nylon, PET are suit for spinning, but those materials are solvent-resistant, and need to use benzene or other strong solvent and heating to dissolve.

High-impact polystyrene (HIPS) not only shows good mechanical properties and spinning performance, but also can quickly dissolve in non-toxic solvents at room temperature, such as limonene. This material melts under 150~180 Celsius degree, starts thermal decomposition at 300 Celsius degree, and have good mobility when it was heated to 200 Celsius degree. HIPS material was modified by adding butadiene to increase the toughness of materials and impact resistance, so HIPS thin filaments have good flexibility. HIPS also has good solubility, it is soluble in aromatic hydrocarbons, chlorinated hydrocarbons, ketones and esters, especially it can completely dissolve in chloroform and limonene without remain. From those properties of HIPS materials, shaped fibers can be easily prepared by melt spinning. The main equipment is a heated nozzle which is heated to the HIPS softening temperature. Feeding from the rear of the nozzle, The HIPS material melts into a viscous fluid and is extruded from the end of the nozzle. When extruded under appropriate cooling conditions, The HIPS fluid hardens into a resilient crude fiber similar in shape to the nozzle and is pulled to small diameter filament under tension. Stretching speed, cooling conditions and extrusion speed together affect the final diameter of the fiber, and the deformation of the fiber cross-sectional shape.

After the preparation of the HIPS shaped fibers, they need to be casted into the PDMS to obtain the PDMS microchannel structure. The HIPS has good compatibility with PDMS, so a normal curing process can be used. Although using HIPS can easily produce filaments with a diameter of only a few tens of micrometers, the filaments embedded in the PDMS after casting may be several centimeters long, and removal of the filaments is a challenge. While normal dissolution method to remove large length-diameter ratio fiber in PDMS is unacceptably slow, and using mechanical extraction may cause damage in channel surface, a PDMS swelling method is developed to remove HIPS fiber inside cured PDMS rapidly.

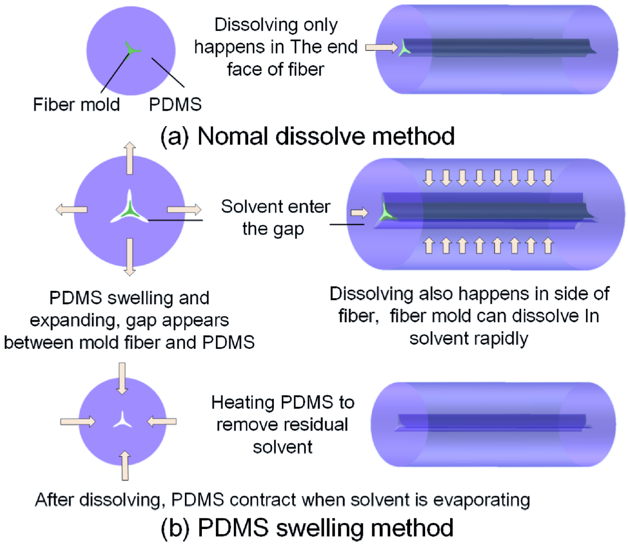

Figure.2 Comparison of normal dissolution method (a), and PDMS swelling method(b). The PDMS swelling method can remove fiber mold in PDMS rapidly by increasing contact area of solvent and fiber.

One method is to increase the contact surface area of the fiber and the solution. After curing, PDMS material is a 3D grid structure, the appropriate solvent molecules can enter the grid structure to cause PDMS swelling, the overall volume would increase. For PDMS with embedded sacrificial cores, the cavity volume will increase during expansion, some gap also appears between channel wall and fiber, solvent can enter the gap and dissolution happens among the whole surface, not only at the end face of fiber (Fig.2). The contact area of solvent and fiber increases by magnitude, leading to the time reduction of dissolution process. PDMS can swell in chloroform and limonene. After swelling, the PDMS becomes brittle, but after volatilization of the solvent, the volume shrinks and the high elasticity state is restored. Based on this property, HIPS materials, which can be rapidly dissolved in chloroform and limonene and is suitable for the spinning process, has great advantages in the PDMS casting-mold release process.

RESULTS AND DISCUSSION

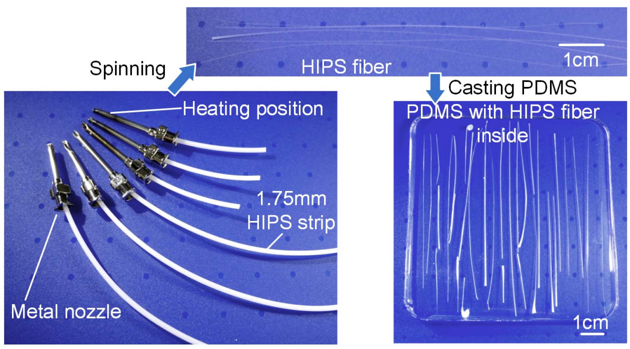

Figure.3 Spinning orifices and HIPS fibers sample.

The preparation of shaped microchannels is divided into the following steps. At first an 1.8mm inner diameter thin-walled stainless steel tube was mechanically molded into spinneret nozzle with designed shape in experiment, resistance heater and platinum resistance thermometer were also mounted on nozzle. An 1.75mm HIPS wire was melted as spinning material (Fig.3). The wire was uniform inserted into the rear of the nozzle, heated to a viscous fluid in front of the nozzle, and pulled out from the nozzle. After drawing the filament was winding on the spool. Then Sylgard® 184 PDMS was mixed at a 10: 1 ratio and the prepared shaped fibers were cast into PDMS. The accumulated stress during the drawing process may cause the fibers to curl after heating, so the curing temperature of the PDMS was controlled below 70 Celsius degree. To remove HIPS fiber in PDMS after casting, limonene or chloroform can be used as swelling solvent. The solidified PDMS was immersed in a hot solvent for several hours, when solution was complete, the colorless transparent solution tended to micro-white. After soaking for 4 hours in hot limonene, cured PDMS length expanded 24% and HIPS mold was dissolved (Fig.4). The demolded PDMS was rinsed with a clean solvent and the residual solvent was distilled off in an oven.

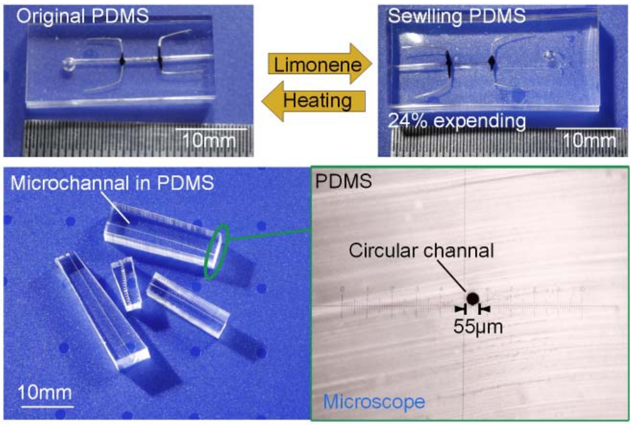

Figure.4 PDMS swelling and expanding in limonene(up). PDMS microchannel after dissolution in limonene(down), with 55μm diameter microchannel .

Micro channels with various shapes of cross-section, from 55μm diameter circular to 220μm length square, were fabricated by the spinning-casting method above. The diameter of filament depends on the heating temperature and spinning speed. Long channels with 1000:1 length diameter ratio were also archived. Some other high profile degree shapes like Y-shape, V-shape, L-shape and C-shape were developed with different shape nozzles, as showed in Fig. 5.

Due to the limitations of the processing conditions, the diameter of the nozzle used in the experiment is about 1 millimeter, and the 100μm level diameter fiber is mainly achieved by stretching the semi-coagulated hot fiber. In future experiment plan, with the using of precision machining methods to obtain more smooth nozzle with smaller diameter, more finely fibers and channels can be produced. As a long-term goal, the using of existing 100μm level nozzle in textile industry can be used to get 10μm size various shaped fibers and microchannels in same level.

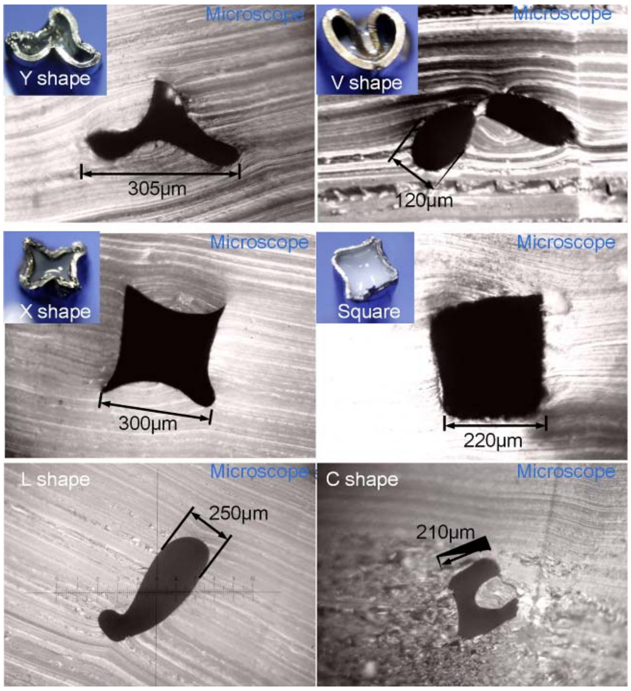

Figure.5 Fabricated specific cross-section microchannel.

On the other hand, with PDMS swelling process, the HIPS fibers can not only be used to build long channels with small diameter, but also for complex designs with various twists like helical pipe and cross channel network (Fig.6). Since the core is dissolved in liquid and discharged rather than mechanically elicitation, the microstructure can be processed by the swelling process even if the inside is tortuous or the inside diameter is larger than the entrance diameter. In experiment, a 100μm diameter helical pipe and an intersecting pipes network were obtained. The HIPS fibers as raw material were hot bended or mechanical bended to obtain the desired shape. The fibers were fused or partially dissolved to be glued as the desired structure, and finally, the PDMS was casted, and the fiber was dissolved and demolded in limonene. This process can be used to realize rapid and simple manufacture of complex 3D microchannel.

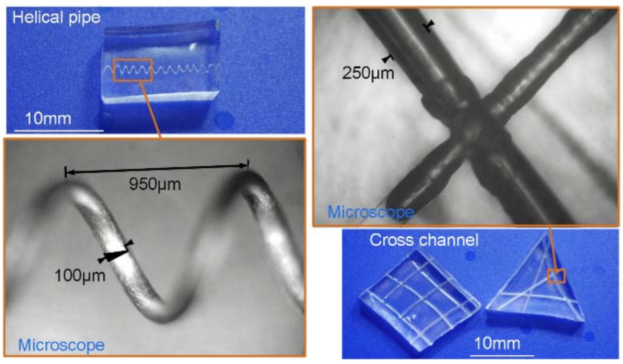

Figure.6 100 μm diameter helical pipe and cross channel network in PDMS.

CONCLUTION

In this paper, a new method for the fabrication of microchannels is reported. The microfibers with shaped cross-section are manufactured by spinning process, and the fiber is casted into PDMS as the sacrificial mold to obtain the microchannel with shaped cross-section. Microchannels with various shapes, from 55μm diameter circular to 220μm length square, from Y-shape, V-shape, L-shape to C-shape cross-section were both fabricated by the spinning-casting method. With the solvent swelling and dissolving process, this method is not only suitable for microchannel with high aspect ratio but also for rapidly fabricating of complex 3D microchannels.

By providing various possibilities in microchannel design and fabrication, this simple and mass productive method has great potentials in microfluidic design. As a long-term goal, by using the existing 100μm level nozzle and 10μm size fiber in textile industry, this method has the potential to achieve 10um level shaped microchannels.

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