Sensors and Actuators B 252 (2017) 785–793

Contents lists available at ScienceDirect

Sensors and Actuators B: Chemical

journal homepage: www.elsevier.com/locate/snb

Enclosed casting of epoxy resin for rapid fabrication of rigid microfluidic chips

Zhen Cheng[a,b], Yin Gu[a], Shanglin Li[a], Yuxi Wang[c], Hongwei Chen[c], Jing Cheng[a,d], Peng Liu[a,*]

[a] Department of Biomedical Engineering, School of Medicine, Collaborative Innovation Center for Diagnosis and Treatment of Infectious Diseases, Tsinghua University, Beijing, 100084, China
[b] Department of Precision Instrument, School of Mechanical Engineering, Tsinghua University, Beijing, China
[c] Department of Electronic Engineering, Tsinghua National Laboratory for Information Science and Technology, Tsinghua University, Beijing, China
[d] National Engineering Research Center for Beijing Biochip Technology, Beijing, 102206, China

ARTICLE INFO

Article history:
Received 23 February 2017
Received in revised form 8 May 2017
Accepted 8 June 2017
Available online 9 June 2017

Keywords:
Epoxy resin
PDMS
Enclosing casting
Chip bonding
Microfluidics

ABSTRACT

A commercially available epoxy resin from Hexion was demonstrated as a complementary material to PDMS (polydimethylsiloxane) for rapidly fabricating rigid microfluidic devices. The fabrication process was streamlined to include the master mold fabrication, one or two times of the PDMS casting, and an enclosed casting of epoxy resin. The use of PDMS as intermediate molds not only guaranteed the easy demolding, but also enabled the novel enclosed casting. This process can produce epoxy resin microdevices in suitable shapes with even surfaces and preformed via holes, eliminating the inconvenient device preparations, such as cutting and drilling. A series of facile bonding methods were developed for epoxy resin with most of common materials used in microfluidics, yielding improved bonding strengths of 261 kPa for epoxy-PDMS, 1185 kPa for epoxy-glass, and 1516 kPa for epoxy-epoxy. To further demonstrate the material versatility, we performed three critical microfluidic applications on epoxy resin-based microdevices, including multilayer pneumatic microvalves, on-chip PCR with improved efficiencies, and ultra-high-speed flow cytometry imaging of microbeads at a flow rate of 8.3 m/s. This study validated the feasibility of utilizing epoxy resin as a routine material for rapidly testing out new designs, for which PDMS may not work, in a laboratory setting.

1. Introduction

PDMS (polydimethylsiloxane) is one of the most widely used materials for fabricating a variety of microfluidic devices [1–4]. It can be easily cast over a mold to replicate down to nanoscale features with a short turnaround time. The elastic PDMS microchips can be peeled off from the mold without any damages, cut into a suitable size or shape using a razor blade, and bonded to another piece of PDMS or glass substrate to form a ready-to-use device. Thus, researchers can adopt an iterative process to efficiently optimize the design with a low cost. Besides the fast fabrication, the elastic nature allows PDMS to be used as diaphragms for on-chip valves and pumps [5,6]. The biocompatible and gas permeable features enable its applications in cell culture [7,8]. Its optically transparent and low auto-fluorescence properties make the observation of fluids within microstructures remarkably easy. As a result, PDMS has been widely recognized as a backbone for rapidly prototyping various microsystems, especially in a laboratory setting. However, more and more studies have demonstrated that PDMS has some intrinsic drawbacks that strongly limit its applicable ranges in microfluidics. For examples, elastic PDMS channels may deform at a high flow rate or under a high pressure in applications such as high-speed flow cytometer [9], inertial focusing [10,11], droplets generation [12], or nanofluidics [13], leading to unstable flow streams. The gas permeability of PDMS may cause severe reagent evaporations during a reaction at an elevated temperature [14]. In addition, its incompatibility with solvents and absorption of small molecules restrict the operation of many chemical reactions on PDMS microchips [15,16]. Therefore, significant efforts have been invested in seeking other plastics that are complementary to PDMS.

Despite a full spectrum of polymers in different mechanical rigidity, light transmission, and surface chemistry could be cho-

* Corresponding author at: Department of Biomedical Engineering, School of Medicine, Tsinghua University, Haidian District, Beijing, 100084, China.
E-mail address: pliu@tsinghua.edu.cn (P. Liu).

http://dx.doi.org/10.1016/j.snb.2017.06.053
0925-4005/

sen for fabricating microfluidic systems [17–19], researchers often hesitate to use thermoplastic materials, due mainly to the lack of simple and rapid prototyping methods like that for PDMS. Most thermoplastic devices were fabricated by either hot embossing or injection molding, which require dedicated and expensive equipment [20,21]. In addition, the sealing of thermoplastic microchips often suffered from limited choices of materials, low repeatability, weak bonding strength, and lengthy operations. One of the most likely solutions to overcome this fabrication challenge is to look for thermoset plastics that can be molded using the casting method [4]. In 2004, Fiorini et al. first proposed thermoset polyester (TPE) as an alternative material to PDMS for microfluidics [22]. TPE can be rapidly fabricated by replica casting in less than three hours, yet offering rigid and stable surface properties. Kuo et al. reported the UV-curable polyurethane methacrylate (PUMA) as a promising polymer for rapid device prototyping [23,24]. The qualification as USP Class VI-compliant guaranteed that the fabrication of microfluidic devices with PUMA can be expected to meet regulatory approval. Meanwhile, thiolene-based optical adhesive (NOA 63/81) was also employed for fabricating microdevices that are resistant in most solvents and compatible with biomedical applications [25]. Although these materials have showed the exceptional advantages in mechanical rigidity and solvent resistance over PDMS, the wide adoptions of these polymers in microfluidics were not very common due to the limited choice of materials for device bonding, low reproducibility in device quality (such as incomplete curing, trapped bubbles, and uneven surfaces), and difficulties in the post preparations of devices (such as cutting, drilling, and gluing). As a result, researchers are still looking for new materials and developing new fabrication protocols for in-laboratory microfluidic applications.

Epoxy is a very broad class of polymers, possessing great advantages in high Young's modulus, solvent resistance, and high light transparency, which have been used with successes in many fields [26,27]. In 2004, Sethu et al. first reported the tests of four different epoxies for micro-casting devices with a 3-h fabrication time [28]. The sealing of the microstructures was achieved either by laminating a flexible film onto the epoxy substrates or by bonding two epoxy chips together with a thin adhesive layer of a Blanchard wax solution. Polymerase chain reaction (PCR) and capillary electrophoresis (CE) were successfully demonstrated on the epoxy resin devices. Other than heating, UV exposure can also initiate the curing of the epoxy resin, which then functioned as a master mold for PDMS replication [29]. More recently, Mogi et al. developed a two-step soft lithography method for rapidly fabricating epoxy resin-based microdevices with preformed inlet and outlet ports [30]. The fabricated structure was easily sealed with a resin, glass and silicon substrate because of the strong adhesion. While these previous studies have successfully established the feasibility of utilizing epoxy resin for microfluidics, the fabrication and the bonding protocols have not been fully explored and verified. As a result, the fabricated epoxy resin microdevices often come with many defects, such as rough edges, uneven surfaces, and trapped bubbles, leading to a low success rate of fabrication. Many functions, such as multilayer on-chip microvalves, were not realized due to the limited choice of the bonding materials. Therefore, in this study, we thoroughly explored the use of a commercially available epoxy resin as a complementary material to PDMS. We developed an enclosed casting method to fabricate epoxy resin devices in suitable sizes with even surfaces and preformed via holes. We also developed a series of bonding protocols for epoxy resin with most of the common materials used in microfluidics and tested the performance of epoxy resin devices in several critical applications, including multilayer PDMS microvalves, on-chip PCR, and ultra-high-speed flow cytometry imaging of beads. This study is a critical step for the transition from elastic PDMS towards rigid thermoset plastics.

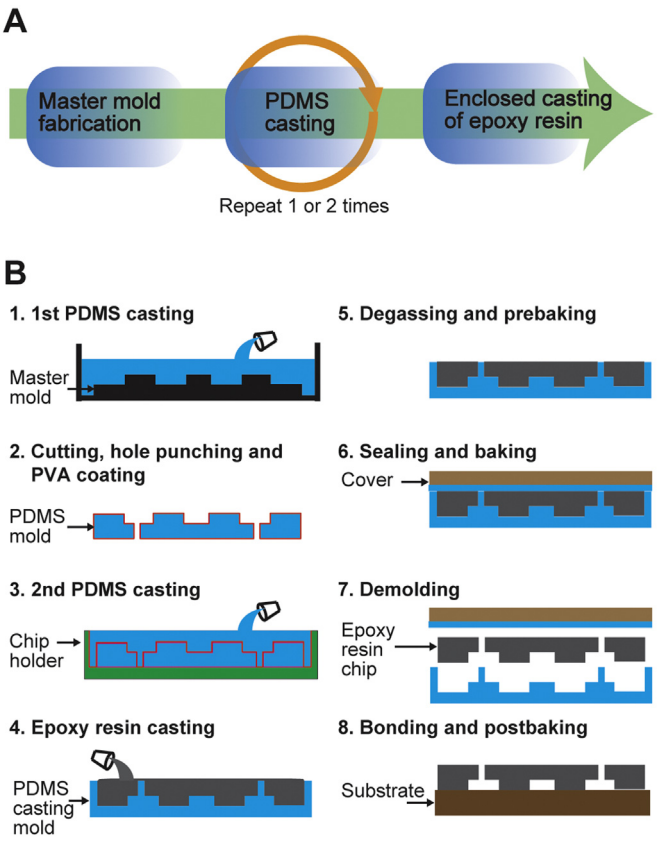

Fig. 1. Fabrication process of epoxy resin. (A) Major microfabrication steps of epoxy resin, including the master mold fabrication, one or two times of the PDMS casting, and the enclosed casting of epoxy resin. (B) Operation process of the PDMS casting and the enclosed epoxy resin casting.

2. Materials and methods

2.1. Fabrication of epoxy resin-based microchips

A commercially available epoxy resin (EPIKOTE™ Resin MGS® RIMR 135 and EPIKURE™ Curing Agent MGS® RIMH 137, Hexion, Columbus, OH) was employed to fabricate a variety of rigid microfluidic devices. The basic microfabrication process of epoxy resin microdevices is shown in Fig. 1A, including the master mold fabrication, one or two times of the PDMS casting, and the enclosed casting of epoxy resin. The fabrication of a master mold can be conducted following the standard protocol of the SU-8 photolithography described elsewhere [10]. Alternatively, the conventional CNC (computer numerical control) machining of aluminum with surface polishing can also produce a durable mold for fabricating a device with a minimum feature size of a hundred microns.

Once the master mold was prepared, the PDMS and the epoxy resin castings were performed following the protocol shown in Fig. 1B. First, PDMS (10:1, PDMS: curing agent, Sylgard® 184, Dow Corning, Midland, MI) was cast onto the master mold. After 2-h incubation at 80 °C, the PDMS mold was peeled off. In the second step, the PDMS mold was cut with a razor blade to the size of the final epoxy resin chip, and via holes were punched using a manual puncher. Then, the PDMS mold was ultrasonically cleaned in ethanol, followed by the oxygen plasma treatment at the 30% full power with a 30-Pa pressure and a 20-sccm flow rate for 30 s (Femto, Diener Electronic, Nagold, Germany). The treated mold