DIRECT, HIGH-SPEED MILLING OF POLYMER MICROCHAMBER ARRAYS

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ABSTRACT

The limitations of semiconductor microfabrication techniques and the growing need for low-cost, disposable lab-on-a-chip platforms demands a method for rapid production of polymer microdevices. Current techniques for polymer device fabrication are impractical for low-volume production and suffer from dimensional constraints. We have developed a method for the fabrication of microchamber arrays using high-speed CNC milling to yield channel widths as low as 125 µm and average surface roughness of 350 nm. This approach has proven to be an invaluable tool for fast and flexible fabrication of polymer microdevices.

INTRODUCTION

Miniaturization of chemical and biological techniques has heralded a multitude of microfluidic applications. Traditionally, glass and silicon have been the preferred substrates for these platforms. Micro-scale features are fabricated using methods borrowed from the semiconductor industry such as wet etching, LIGA, and DRIE, and require expensive, hazardous, and slow processes that severely limit practicality, especially in the early design phases [1]. As a lower cost alternative, polydimethylsiloxane (PDMS) has become a ubiquitous polymer for devices made by soft lithography. Still, this approach requires tedious mold fabrication and yields devices insufficiently robust for applications outside of a laboratory. As the field of microfluidics matures, shifting towards affordable, disposable, and commercially viable platforms, conventional materials and the accompanying techniques are being replaced [2]. Instead, rigid polymers such as PMMA, polycarbonate, and cyclic olefin copolymers (COC) are preferred and techniques such as micromolding, laser etching, and direct milling have emerged as effective solutions.

Micromolding by injection molding and hot embossing are ideal for high-volume production of devices but can suffer from de-molding challenges. Also, these methods require a master, which can be slow to fabricate and therefore not amenable to fast prototyping. Laser etching is fast and affordable but incompatible with many materials and presents difficulties achieving accurate depths and smooth surface finish. Direct milling is a less common approach based on directly machining a polymer substrate and has been demonstrated for microfluidic applications [3]. Tool paths are programmed for CNC milling using CAD-CAM software and design changes are implemented by altering simple code. After experimenting with the above techniques, we found direct milling to be the most promising for fast turnaround (e.g. 5 min per device), wide-ranging dimensions, consistency, and minimal cost. Here we discuss the direct milling process applied to developing microchip-based diagnostic devices.

MATERIALS AND METHODS

We used a 3-axis vertical milling center (Haas, OM-1A) capable of accurate positioning within 10 µm and repeatability of 6 µm. The spindle operates at speeds up to 30,000 rpm, enabling the use of miniature end mills (Harvey Tool) and drill bits (Drill Bit City) with sub-millimeter diameters. Our substrate material of choice was Zeonor 1420R (Zeon Chemicals), a biocompatible cyclic olefin copolymer with a relatively high glass transition temperature of 136°C. Other materials tested include PMMA and polycarbonate.

A custom aluminum fixture (Figure 1) was milled and used to align and rigidly hold the workpiece, since small part deflections can easily damage the fragile tooling. A corner relief was pocketed into the fixture to allow repeatable positioning. Strap clamps were laser cut from 0.125” acrylic, which was chosen to avoid marring the surface of the workpiece. These are configured in a third-class lever arrangement and the screws can be hand-tightened to provide ample clamping force.

Prior to milling, each tool is zeroed to the top surface of the workpiece. This was accomplished using a multimeter to detect electrical conductivity between the tip of the tool and the base of the fixture by moving in 0.0001” increments. The tools were then offset by the thickness of the workpiece, which was precisely measured using a dial probe indicator.

Microchamber designs were creating in Solidworks and transferred to MasterCAM for generating toolpaths and outputting g-code. Climb milling was used to minimize burr formation and bursts of compressed air were used to clear chips. Finished devices were cleaned with ethanol and dried with compressed air or nitrogen.

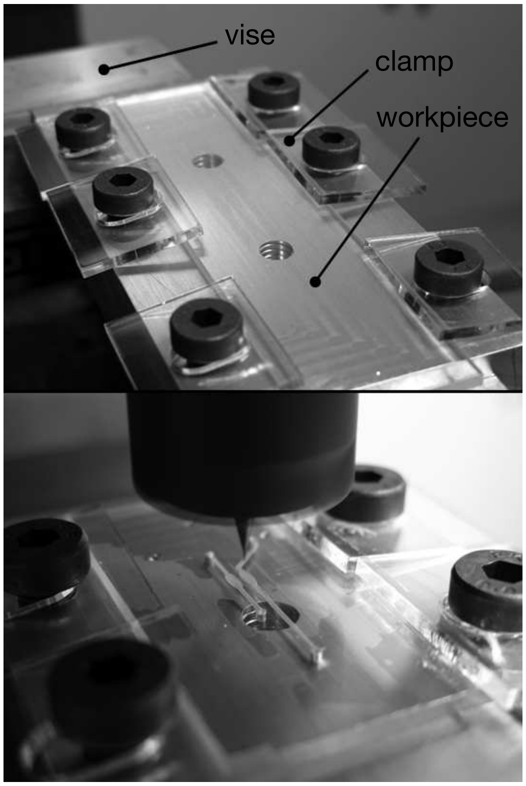

FIGURE 1. An aluminum fixture allows repeatable positioning and acrylic clamps tightly grip workpiece (above). A 125 µm diameter endmill pockets a PCR device in less than 5 min (below).

Back-end processing for the milled devices include enclosing the channels and sealing the ports once loaded with a sample. Our channels were encapsulated in a 2 min process by thermal bonding of a 100 µm Zeonor film using a hot press operating at 100 psi and heated to 140°C. Sealing the device is best accomplished with curing PDMS in the ports to prevent evaporation and suppress bubble formation.

EXPERIMENTAL RESULTS

A four-chamber device (Figure 2) was fabricated for an application we are pursuing involving infrared heating of multiple aqueous samples in an array of 1 µL microchambers. It features 250 µm wide, 125 µm deep lead-in channels and 500 µm wide, 1 mm deep reaction chambers milled at 30,000 and 20,000 rpm, respectively. Other geometries creating by direct milling include microchannel electrophoresis devices requiring tooling as small as 125 µm in diameter. Maximum channel depths are typically three times the diameter of the tool but have been demonstrated up to ten times the diameter with specialized long reach tooling. Minimum channel depths are determined by the z-axis resolution of the milling machine and the precision of the tool zero. Total machining time ranged from 5 to 10 min depending on the feature complexity and tool size.

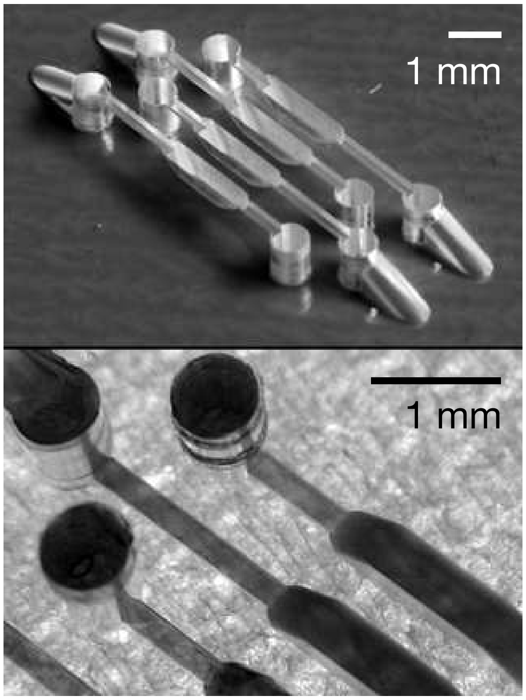

FIGURE 2. The four-chamber device was milled from a 2 mm-thick COC substrate at spindle speeds up to 30,000 rpm and feed rates around 20 inches per min. The milled part (above) is sealed by thermal bonding of a 100 µm film and shown filled with a dye solution (below).

Bonded devices have been used repeatedly without suffering delamination or mechanical damage. Surface roughness was measured using a Taylor Hobson Talysurf Surface Profilometer. A sample of Zeonor 1420R was machined at various depths using a 250 µm diameter 4-flute square end mill operating at 30,000 rpm and tilt-corrected profile data was collected along the bottom of the channels. Average surface roughness was found to be roughly 350 nm, which is an order of magnitude lower than typical reported values for machined devices [2]. Still, surface roughness and other imperfections can lead to trapped air bubbles upon filling with a liquid. Sealing the ports with PDMS helps prevent the expansion of any entrained gas if the device is heated. Long tool life was observed after repeated operations given appropriate machining parameters.

CONCLUSION

By applying machining techniques to the fabrication of microfluidic devices, we have demonstrated an effective way to produce geometries with dimensions and aspect ratios impossible with other methods. With careful fixturing and tool zeroing, highly precise parts can be attained in a short period. Tweaks to the design and machine settings, such as feedrate and spindle speed, can be made on-the-fly through software to allow optimization of part quality and efficacy for its intended application.

Drawbacks to direct milling include burr formation and compromised optical clarity. We found that burrs can be minimized by climb milling all edges. Remaining burrs are removed with bursts of compressed air. Precision is limited by the user's ability to set accurate zeroes and the machine's positioning resolution. Additionally, this approach is not economical for higher volume production. Direct milling requires higher than average spindle speeds and therefore is not possible with most standard machine shop equipment. A spindle speeder, or high speed spindle attachment, is an option for achieving higher spindle speeds in order to use the required small-scale tooling.

Given the right equipment, direct milling is a straightforward and effective method for fast turnaround microfabrication. We have successfully created several different devices from multiple materials and will continue to push the limits of this technique.

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