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Magnetic field-assisted finishing of a mold insert with curved microstructures for injection molding of microfluidic chips

Jiang Guo*, Kui Liu, Zhenfeng Wang, Guan Leong Tnay

Singapore Institute of Manufacturing Technology, 73 Nanyang Drive, Singapore 637662, Singapore

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A B S T R A C T

Microfluidics has a wide application ranging from ink-jet printing to lab-on-chip in biomedical research and diagnostics chemical processing. For many disposable applications, injection molding process is usually adopted for mass production of microfluidic chips. Therefore, fabricating high quality mold inserts with precise geometry and smooth surface becomes a challenge. Recently, precision machining technologies such as cutting and milling have been increasingly employed for fabricating microstructures in the size of tens to hundreds of micrometers considering the advantages in design flexibility, productivity and economical cost. However, due to the limitation of the achievable surface quality attributed to defects such as burrs and tool marks, a post-polishing process which can maintain the shape of micro features while improve surface finish becomes an indispensable step. In this paper, magnetic field-assisted finishing (MFAF) method was firstly adopted to finish a mold insert which has curved microstructures on the surface for injection molding of microfluidic chips. The working principle of the configuration was illustrated, and the experimental setup and conditions were detailed. Abrasive flow simulation was conducted to analyze material removal around microstructures and the results were verified by experiments. When the abrasive flow direction was perpendicular to the side of microstructures, abrasives became easy to access to the corners of the microstructures and less material was removed. According to the results of material removal analysis, the polishing path was planned by dividing the mold insert surface into 5 zones to ensure abrasive flow direction perpendicular to the side of microstructures. The results show that the heights of the microstructures were maintained although the edges were rounded after polishing while the surface roughness was reduced to approximately 0.11 µm Ra, achieving a mirror finish. The surface quality before and after polishing regarding microhardness, residual stress, friction and wear characteristics were compared.

1. Introduction

Microfluidic devices consist of sub-micrometer and sub-millimeter sized channels that can be used to control the movements of miniscule amounts of fluids for continuous sampling and real-time testing of air and water samples. The applications of microfluidic devices are increasingly diverse, ranging from ink-jet printing to lab-on-chip and are widely used in biomedical research and diagnostics, chemical processing, water monitoring/processing, and alternative energy exploitation [1,2]. Many research activities are investigating the manufacturing of integrated microfluidic devices on a mass-production scale with relatively low costs [3]. This is especially important for applications where disposable devices are used for medical analysis. Injection molding, as one of the key technologies, is usually adopted for mass production of microfluidic chips made of thermoplastics (e. g. polymethylmethacrylate (PMMA), polycarbonate (PC), and cyclic olefin polymers. (COP) or copolymers (COC)) which are used for many fluidic samples analysis [4]. To guarantee a high quality of mass fabricated microfluidic chips, fabricating high quality mold inserts with precise geometry and smooth surface becomes essential.

In general, there are two ways to fabricate the mold inserts. One way is to use the microelectromechanical systems (MEMS) methods involving photolithography, etching and electrodeposition. It is usually used to fabricate microstructures in size less than a few micrometers on mold insert surface [5]. For instance, Becker et al. used synchrotron radiation lithography, galvanoforming, and plastic molding (LIGA process) to fabricate microstructures with high aspect ratios and great structural heights [6]. Friend et al. used photolithography to form a mold insert for casting the PDMS structure [7]. The other way is to use machining technologies such as precision cutting and milling. It is employed when microstructure size is in tens to hundreds of micrometers. It has the advantages of good design flexibility, short fabrica-

* Corresponding author.
E-mail address: guojiang3302@gmail.com (J. Guo).

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tion time and low cost. Besides, it is capable of fabricating complicated structures with multi-steps on substrate surface. Jung et al. used micro end-mills to machine mold inserts for fluidic channel of polymeric biochips [8]. Mecomber et al. proposed an improved approach for the generation of aluminum masters used in the replication of polymer-based microfluidic devices [9]. For many microfluidics applications, surface quality is essential to device performance. The mold insert is always required to have a mirror surface finish and accurate dimension of micro features so as to guarantee a precise flow control of micro fluid. However, due to the limitation of the achievable surface quality by machining processes attributed to defects such as burrs and tool marks, a post-polishing process which can maintain the shape of micro features while improving surface finish is therefore necessary.

To date, as it is difficult for polishing tool to access the recessed corners of microstructured surface and subsequently remove materials uniformly in a high efficiency, there are no proper solutions to polish microstructured surfaces. Manual polishing is usually adopted by most of the manufactures. However, even by skilled workers, the corners of microstructures cannot be accessed. Furthermore, due to the non-uniform material removal, additional waviness can be generated on workpiece surface which will result in failure during bonding process. In recent years, although some tool-based polishing methods such as bonnet polishing [10], Magnetorheological Finishing (MRF) [11], miniaturized vibrating tool polishing [12,13], conical pin-type and conical wheel-type tools polishing [14] and even fluid jet polishing [15] have been reported, it is still difficult for them to access the corners of microstructures and remove material uniformly. Therefore, a flexible tool capable of fitting the geometry of the microstructured surface is preferable.

Magnetic field-assisted finishing (MFAF), in which magnetic abrasives are employed as the flexible tool, seems to be a good candidate to solve this problem. The utilisation of MFAF allows for challenging geometry to be accessed for workpiece. Compared with the above-mentioned polishing technologies, MFAF enables better geometry conformant capability for microstructured surface [16]. Kim et al. used magnetorheological fluid mixed with abrasives as a polishing tool to polish three-dimensional silicon channel [17]. Yin et al. studied polishing characteristics and mechanisms in vibration-assisted magnetic abrasive polishing (VAMAP) and realized the polishing of a 3D micro-curved surface [18]. Guo et al. proposed a new vibration-assisted magnetic abrasive polishing method to finish microstructured surface. The method can improve the surface finish while maintain the profile of the microstructures [19]. It also exhibits good flexibility in controlling process parameters such as magnetic abrasive composition and polishing force, to reach target user requirements in work tolerances and surface conditions [20]. However, there is no research addressed surface finishing of curved microstructures.

This paper presents the first trials on finishing of mold insert which surface has curved rectangular microstructures for injection molding of microfluidic chips using magnetic field-assisted finishing (MFAF) method. It began with the design of the mold insert and sample preparation by precision milling. Then the working principle of the configuration was illustrated, and the experimental setup and conditions were detailed. Next, material removal analysis around microstructures was conducted by abrasive flow simulation and verified by experiments. After that, according to the results of material removal analysis, the polishing path on mold insert surface was planned. Finally, the finishing results regarding surface topography, profile, surface roughness, microhardness, residual stress, as well as friction and wear characteristics were explained.

2. Sample preparation

2.1. Designed feature of the mold insert

Fig. 1 shows the designed feature of the mold insert for fabricating microfluidic chips. The size of the mold insert is 75 mm×25 mm. It is used in injection molding process to replicate polymer microfluidic chips called Y-reactor which consist of two fluid inlets, one fluid outlet, and a serpentine channel as reaction chamber. The flow delay length is about 100 mm. The microstructure on the mold insert has a height of 100 μm and a width of 100 μm which resulting in an aspect ratio of 1:1.

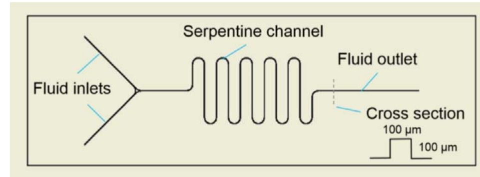

Fig. 1. Designed feature of a mold insert for fabricating microfluidic chips. (The size of the mold insert is 75 mm×25 mm. The microstructure size is 100 μm×100 μm.).

The mold insert material is a kind of fine grain aluminum alloy, RSA 905, which has a fine microstructure achieved by a rapid solidification melting process. As a robust alloy, it demonstrates superior mechanical properties such as hardness and strength than conventional aluminum alloys, and no heat treatment is needed to achieve these properties [21]. Besides, it shows a good machining property by diamond turning and abrasive polishing [22,23]. Currently, it has already found application in mold industry, especially for precision optics. Compared with stainless steel such as Stavax [24] which is usually adopted as mold insert material, RSA 905 is not strong enough. However, it could be considered for low volume production.

2.2. Precision milling

Prior to polishing, the material was processed by precision milling to fabricate rectangular microstructures on mold insert surface using a precision machine tool (MILLTAP 700, DMG MORI SEIKI Co., Ltd.). Two types of end mill tools made of tungsten carbide with diameters of 3 mm and 1 mm were used to cut the material. The process was planned in two steps. Firstly, ϕ 3 mm end mill tool was used to remove the material on the flat surface. Then ϕ 1 mm end mill tool was used to remove the material around the microstructures. The tool paths for ϕ 3 mm and ϕ 1 mm end mill tools were calculated using a CAM software as shown in Fig. 2(a) and (b), respectively. During precision milling process, the feed rate was set to 1000 mm/min. with a feed depth of 5 μm. The results after precision milling process regarding surface roughness and step between ϕ 3 mm and ϕ 1 mm end mill tools will be detailed in Section 6.1.

3. Experimental

3.1. Working principle of the configuration

In general, MFAF method utilizes magnetic field to control and manipulate magnetic abrasives to remove materials from surface of workpiece. Here, a dual magnetic roller design was adopted to generate the magnetic field. It was designed in a manner that exhibits differential magnetic flux densities at various target positions around the rollers, enabling a reforming mechanism of the magnetic abrasives at each revolution [25]. A schematic illustration of the MFAF configuration is shown in Fig. 3(a). There is a small gap between the two rollers to prevent contact and the rotation direction of the rollers is opposite to each other (i.e. one clockwise and the other counter clockwise). The magnetic abrasives formed between the two rollers were used as the polishing tool to remove the materials. Magnetic abrasives consist of carbonyl iron powder (CIP), abrasive particles, and a disperse medium (oil or water). As shown in Fig. 3(b), magnetic flux lines connect the two rollers and generates a closed magnetic circuit, thus the leak of magnetic flux is minimized. As a result, a high magnetic flux density is generated at the finishing area (see Fig. 3(c)). The

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