ARTICLE IN PRESS

Precision Engineering xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Precision Engineering

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

On form accuracy and surface roughness in micro-ultrasonic machining of silicon microchannels

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ARTICLE INFO

Keywords:
Surface roughness
Overcut
Stray cut
Medium viscosity
Feature plot

ABSTRACT

Accuracy in manufacturing microchannels is important in order to achieve their intended function. Smooth and high aspect ratio microchannels on silicon wafer substrate are needed in the heat removal application in various microelectronic components. Generally, etching techniques are used to fabricate silicon microchannels; however, the maximum achievable limit for the channel depth is a major concern. Micro-ultrasonic machining (micro-USM) is capable of machining high aspect ratio microchannels on hard and brittle material such as silicon, glass, ceramics, etc. However, achieving reasonable form accuracy and surface roughness of the microchannels is challenging. Overcut and edge damage (stray cut) are undesirable for precision machining while surface roughness of the microchannels can be set at an optimized value to attain maximum heat transfer. In the present study, silicon microchannels were fabricated using the micro-USM technique. In order to improve the precision and quality of the fabricated silicon microchannels in terms of surface roughness, overcut and stray cut; viscous fluids with different viscosities were considered for investigation in combination with other machining conditions. The experimental investigation revealed that using low viscous fluids yields better surface roughness compared to high viscous fluid; however, overcut and stray cut were minimized while using high viscous fluids. Machining at higher feed rates could minimize the surface roughness, over cut and stray cut irrespective of the abrasive concentration percentage. Possible interactions between the tool, abrasive and workpiece in the machining zone were analyzed vis-à-vis the experimental results.

1. Introduction

Focus in improving the capabilities and accuracies in micromachining has been on the rise with an increase in the demand for miniaturized components in various applications such as lab-on-chips, micro heat exchangers, electronic systems, micro-reactors, micro-electromechanical systems (MEMS), micro-fluidic systems, etc. Fabrication of precise microchannels for the intended components is one of the most primary requirements in all such applications. Microchannels have attained prominence in miniaturization, especially in the electronic industry, due to their capability of removing high heat fluxes. Aluminum, copper, stainless steel and silicon are commonly used substrate materials to fabricate microchannels due to their good mechanical and thermal properties. However, silicon microchannels are popular in heat transfer applications in microelectronic devices.

The first silicon microchannel was developed by Tuckerman and Pease in 1980's by an orientation dependent etching technique [1]. These microchannels were used to remove a high heat flux (~ 790 W/ cm^2) from a small area with deionized water as a working fluid. Later, research was mostly focused on fabrication of precise microchannels with different cross-sections, aspect ratios and surface conditions using different micromachining techniques such as micro-EDM, micro-ECM, micro-LBM, micro-USM, LIGA, photolithography, micro-cutting, micro-casting, etc. [2,3]. Heat transfer characteristics were investigated experimentally by Qu et al. and compared the results with numerical data on trapezoidal silicon microchannels fabricated by anisotropic etching technique [4]. They reported significant difference between these results which was attributed to the surface roughness of the microchannel walls. Wu and Cheng had fabricated differently sized silicon microchannels of trapezoidal cross-section by varying surface conditions by the wet etching technique and studied the heat transfer characteristics [5]. The studies revealed that both the surface roughness and geometric parameters of the microchannels had significant effect on their heat transfer characteristics. Attempts were made to improve the surface finish of the walls and bottom of the silicon microchannels by (i) varying the temperature of silicon etchant, (ii) controlling the composition of the etchant and (iii) orientation of the masking pattern [6].

The wet and dry etching techniques are commonly used to fabricate

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https://doi.org/10.1016/j.precisioneng.2018.04.014
Received 14 January 2018; Received in revised form 10 March 2018; Accepted 16 April 2018
0141-6359/

Please cite this article as: Sreehari, D., Precision Engineering (2018), https://doi.org/10.1016/j.precisioneng.2018.04.014

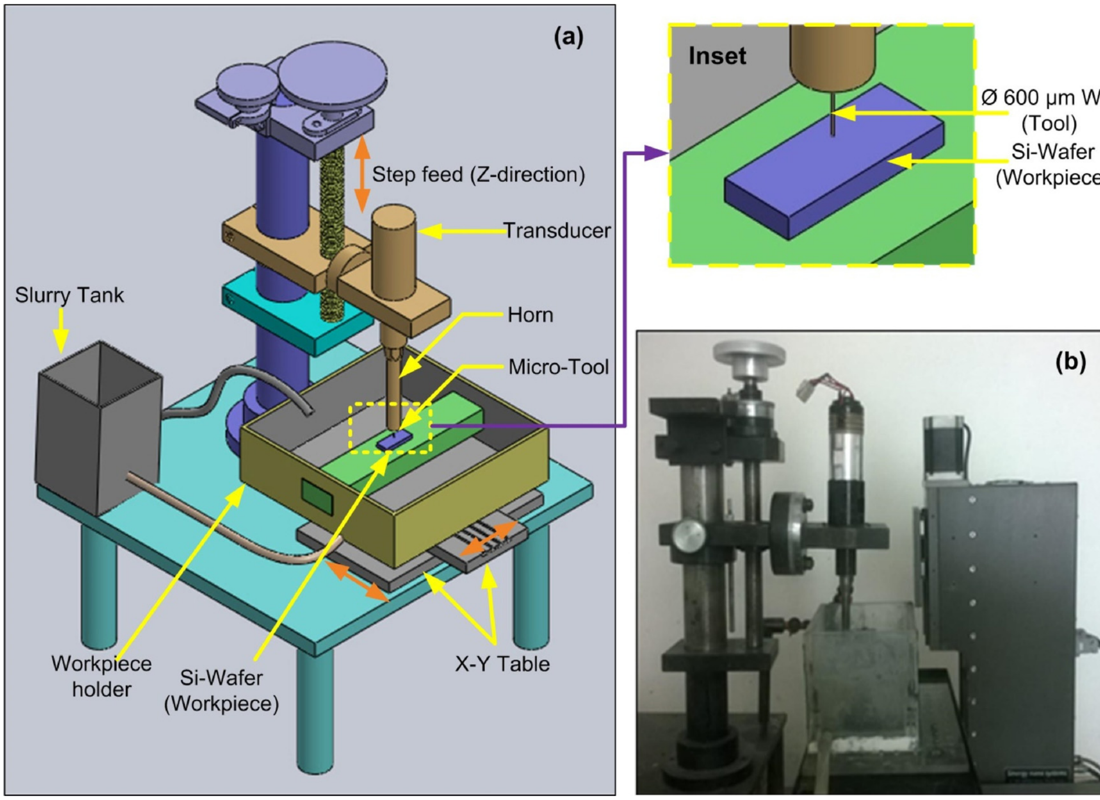

Fig. 1. (a) Schematic of the micro-USM setup used for the trials (inset: enlarged view of the machining zone), (b) Image of the experimental setup.

silicon microchannels; however, these techniques are dependent on orientation and etch temperature. Further, etching techniques require clean room environment; the chemicals which are used for etching could create a hazardous environment. In photolithography technique, surface roughness may no longer be an issue, but the major limitation is the low aspect ratio. Practically, 3D microchannels cannot be machined using such techniques and it is difficult to control the desired depth of the channels. The 3D microchannels could be effectively machined by micro-USM technique as demonstrated by some authors [7–10]. The 3D microchannels fabricated using micro-USM on glass and silicon were investigated in terms of surface roughness, material removal rate and tool wear rate by varying different process parameters [10]. Surface roughness characteristics on (100) silicon wafers machined using micro-ultrasonic technique were studied and showed that the surface roughness depends mainly on the depth of cut and the size of the abrasive particles in the slurry mixture [11].

Several attempts were made to improve the surface finish of the profile generated by micro-USM. Abrasive Flow Machining (AFM) technique was used to improve the surface quality of the SiC microchannels fabricated by micro-USM and the authors had reported a significant improvement (approximately 59.3%) [12]. Few researchers had applied a hard wax coating on the substrate material to control the crack initiation and hence to control the surface quality while fabricating microholes on the glass [13]. The authors claimed that the wax coating on the substrate helps in protecting the surface by minimizing the crack initiation. Chemical assisted machining was explored by Choi et al. in order to improve the surface integrity of ultrasonic machined profile [14].

Form accuracy of the microchannels in terms of overcut and stray cut, along with surface quality, are important issues that need attention. In micro-USM, the surface quality, overcut and stray cut are significantly affected by the abrasive particle movement [15]. Further, abrasive movement depends on the viscosity of the slurry medium and on the slurry concentration. The viscosity effect of the slurry was either neglected or not given priority in the previous studies as in most of the investigations water was used in the slurry medium [16]. However, it was also reported that there was an improvement in the surface finish while using oil-based abrasive slurry than the water-based abrasive slurry [17]. It was further shown that the workpiece feed rate also had a considerable influence on surface roughness, overcut and stray cut of the glass microchannel fabricated by the micro-USM [18].

In the present study, the effect of slurry viscosity, abrasive slurry concentration and workpiece feed rate on surface quality, overcut and stray cut of the silicon microchannel were investigated. The experimental methodology adopted and the results obtained have been presented with relevant analyses.

2. Methodology

2.1. Selection of process parameters

Abrasive slurry in USM acts as a coolant for the horn, tool and workpiece; it also supplies fresh abrasives to the cutting zone and removes debris from the cutting area [19]. It should also provide good acoustic bond allowing efficient energy transfer between the tool, abrasive and the workpiece. In general, water is used as a slurry medium. In the present study, three different slurry media were used to investigate the effect of viscosity of the slurry on the improvement of surface quality and form accuracy of the machined microchannel. Three different viscous fluids namely – palm oil, transformer oil and water, having relatively high, moderate and low viscosity, were taken as slurry medium for the trials, these media are low cost and easily available. The dynamic viscosities of these fluids at 30 °C are 57.85 mPa.s, 13.44 mPa.s and 0.7972 mPa.s, respectively [20]. It was reported that slurry concentration and workpiece feed rate are the other parameters that significantly affect the machining process [18]. Therefore, these two parameters were considered while investigating the performance of the three slurry types.