Ultrasonics 57 (2015) 57–64

Contents lists available at ScienceDirect

Ultrasonics

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

Tool wear studies in fabrication of microchannels in ultrasonic micromachining

Manjot S. Cheema *, Akshay Dvivedi, Apurbba K. Sharma

Department of Mechanical and Industrial Engineering, Indian Institute of Technology, Roorkee 247667, India

ARTICLE INFO

Article history:
Received 9 January 2014
Received in revised form 4 June 2014
Accepted 21 October 2014
Available online 31 October 2014

Keywords:
Ultrasonic micromachining
Microchannels
Tool wear
Form accuracy

ABSTRACT

Form accuracy of a machined component is one of the performance indicators of a machining process. Ultrasonic micromachining is one such process in which the form accuracy of the micromachined component significantly depends upon the form stability of tool. Unlike macromachining, a very small amount of tool wear in micromachining could lead to considerable changes in the form accuracy of the machined component. Appropriate selection of tool material is essential to overcome this problem. The present study discusses the effect of tool material, abrasive size and step feed in fabrication of microchannels by ultrasonic machining on borosilicate glass. Development of microchannels using ultrasonic micromachining were rarely reported. It was observed that tungsten carbide tool provided a better form accuracy in comparison to the microchannel machined by stainless steel tool. The tool wear mechanism in both materials is proposed by considering scanning electron micrographs of the tool as evidence. A one factor at a time approach was used to study the effect of various process parameters.

1. Introduction

Tool wear can be considered as one of the most important parameters which decides the form accuracy of a machined component. Form accuracy, on the other hand manifests as how close the machining process replicated the dimensions of cutting tool on the workpiece surface [1]. The efficacy of ultrasonic micromachining can also be measured by form accuracy of the machined component. As the tool gets worn out with time, a noticeable change is observed in form accuracy forcing the component towards rejection in the quality check. However, form accuracy can be achieved significantly by controlling and maintaining the tool shape and size. Tool material properties are important parameters effecting the tool wear. Maintaining form accuracy becomes even more challenging while machining at micro levels.

Flexibility and feasibility of machining micro components using ultrasonic machining (USM) have already been demonstrated [2–4]. Hard and brittle materials like glass, silicon wafers and ceramics could easily be machined by USM in the micro domain too [5]. Moreover, while compared to chemical methods of etching and lithography, USM is preferred as a cleaner and faster process. Extensive work have been reported in macro drilling of various hard and brittle materials [6]. Studies were carried out on tool wear at macro levels. In one of the studies, the tool wear pattern was divided into two types – lateral wear and longitudinal wear [7]. Lateral wear at the tool edges occurred due to the abrasive rubbing phenomenon between the tool and workpiece walls. Lateral wear was also found responsible for reduction in tool diameter. On the other hand, longitudinal wear was responsible in reduction of tool length which occurred due to microchipping and cavitation phenomenon [8]. The complete tool wear during USM of macro holes was thus, a combination of both the wear patterns. Some researchers reported that with an increase in machining time, microhardness of the tool was found to be more at the edges in comparison to the middle part. Plastic flow and work hardening were found to be the major reasons for increased hardness [9].

In macro machining, if the tool gets slightly worn out, the machined product can still fall in the desired range. However, in case of machining in the micro regime, for example, fabrication of components like microchannels and microholes, the form accuracy gets affected drastically with minimal tool wear. Consequently the parts are liable to be rejected. One of the ways for achieving desired form accuracy is to minimize tool wear to the extreme possible.

Tool wear in USM mainly depends upon a number of factors like workpiece material, tool material, amplitude, applied frequency of vibration, abrasive type, abrasive size, static load and concentration of abrasive particles. Proper combination of the above mentioned parameters is essential to minimize the eventuality

---

* Corresponding author.
E-mail address: manjotcheema@hotmail.com (M.S. Cheema).

http://dx.doi.org/10.1016/j.ultras.2014.10.018
0041-624X/© 2014 Elsevier B.V. All rights reserved.

wear. But the tool material is the most crucial parameter deciding the wear. Nimonic alloys, thoriated tungsten, tungsten carbide (WC), high speed steel, silver steel, titanium, maraging steel and mild steels have been the most commonly used tool materials for ultrasonic macro machining [10]. While macro drilling, it was reported that stainless steel (SS) tool is far better than WC tool [7–9,11]. This implied that SS could be an excellent candidate for ultrasonic micromachining. It is easily available and is a cost effective solution for machining. The ultrasonic micromachining can be differentiated from the macromachining by the size of machined features developed, which is generally less than 1 mm.

However, conflicting opinions were revealed for SS tool in USM at micro levels [2,3,12–14]. Some studies in ultrasonic micromachining include development of models for predicting tool wear [10].

These contradictions encouraged the present study on tool wear of SS and WC tool while fabricating microchannels on borosilicate glass. The tool wear effect on the form accuracy of developed microchannels was investigated in this study. Further, this study deals with identification of tool wear mechanism. Subsequently this article defines the type of tool material for microchannel fabrication. A one factor at a time approach was used to study the effect of step feed and abrasive size on the form accuracy of developed microchannels using SS and WC tool.

2. Methodology

A layer by layer machining approach was used for machining a 10 mm long microchannel using USM. In USM, a solid cylindrical tool can be used in the same method as an end mill in milling process. Cylindrical tool provided the flexibility of machining in various axis and number of profiles could be developed. In the present study SS and WC tools of same diameter were used. The experimental details are given in Table 1.

A *XY* axis (built in house) was used to provide motion to the borosilicate glass workpiece. The glass workpiece was mounted on a fixture. Part programming was carried out through a dedicated software of the 3 axis programmable *XY* stage. The *XY* stage had an accuracy of 0.1 μm. Machining was completed after a number of repeated cycle with a step feed in *Z* axis of 5, 10 and 15 μm in each pass. A depth of 300 μm was achieved while using each tool material. Silicon carbide abrasive slurry (15% by weight) was kept on flowing through the tool and the workpiece gap.

The width and depth of micro channel periphery were measured at 50× magnification on the dedicated software of microscope (Model: Dewinter DMI premium). The top view and side view of the tools were captured by a LEO scanning electron microscope (SEM), (Model: LEO 435VP). The tool images were captured by a stereo zoom microscope (Model: Nikon SMZ-745 T).

Table 1
Parameters used in ultrasonic micromachining.

Experimental conditions	
Power	800 W
Vibration frequency	20 kHz
Amplitude of applied vibration	20–30 μm
Abrasive material	Silicon carbide
Abrasive size (mesh)	1800#, 1000# and 800#
Workpiece material	Borosilicate glass
Tool material	(i) Tungsten carbide, (ii) stainless steel
Tool diameter	Ø 600 μm
Feed in *X* direction	30 mm/min
Step feed in Z direction	5, 10, 15 μm
Total depth given in *Z* direction	300 μm
Slurry medium	Water
Slurry concentration	15% Abrasive by weight

3. Mechanism of tool wear

In USM, when the vibrating tool goes up to the topmost position. It accumulates abrasive particles in between the tool and workpiece. The tool when comes down, strikes the abrasive particle which further strikes the workpiece. This gap created between tool and workpiece is known as the working gap (Fig. 1). The cavity (Area ABCDEF) developed during machining is always slightly bigger than the tool size owing to abrasive movement adjoining the tool surface. The gap in this enlarged cavity between the workpiece walls and the tool boundary is known as the lateral gap which is created due to the exit of abrasive particles as shown in Fig. 1. The motion of abrasive particles from working gap to lateral gap can be classified into the following three zones which exhibited different mechanisms (Fig. 1):

1. Pure hammering + cavitation (zone-1).
2. Hammering + abrasion + cavitation (zone-2).
3. Pure abrasion + rolling (zone-3).

In USM, the most dominant mode of material removal is the hammering action [6]. As the vibrating tool strikes the abrasive particles, the entire energy is transmitted to the abrasive particles. The abrasive particles further strike the workpiece material causing microcracks and removed material in the form of microchips. Further cavitation is another phenomenon which assists the material removal. Cavitation collapse also leads to acceleration of abrasive particles [15]. Due to repeated tool impacts on the abrasive particles and cavitation, the tool wears. This tool wear is prominent once the tool material crosses its fatigue limit [12]. This phenomenon's predominantly occur in the zone-1 which is below the tool surface in the working gap. As fresh slurry is supplied continuously, the abrasives after striking in zone-1 move towards zone-2. Edge wear of tool has also been reported [7]. The vibrations of tool and constant supply of fresh slurry creates high pressure in zone-1. The previous abrasive particles which strike the glass surface are pushed to different sides of the tool. This resulted in entry of some abrasives towards lateral gap through zone-2.

During this movement of abrasives towards the lateral gap, the sharp edges of tool abrade in zone-2. The sharp edges of the tool became blunt after some time. Hence rounding of edges takes place. Simultaneously the abrasive particles came in contact at surface of the rounded edges of the vibrating tool, due to which

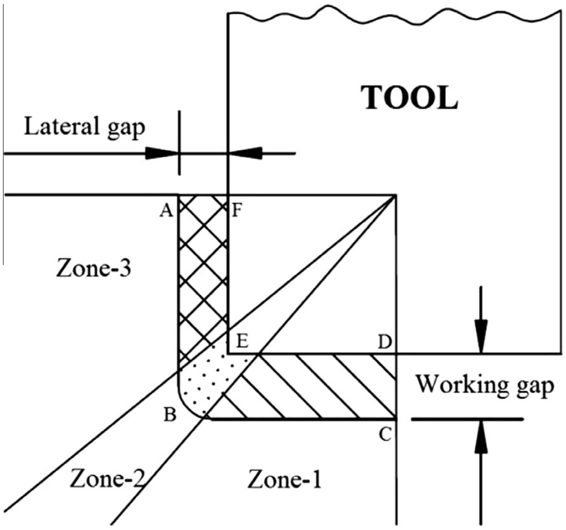

Fig. 1. Schematic showing the different zones of tool wear.