Chapter 27
On Performance Evaluation of Helical Grooved Tool During Rotary Tool Micro-ultrasonic Machining

Sandeep Kumar and Akshay Dvivedi

Abstract The present investigation reports on reduction of width overcut (WOC) and edge chipping in micro-channels developed by rotary tool micro-ultrasonic machining using helical grooved tool. The experiments were conducted to evaluate the effectiveness of the helical grooved tool in terms of WOC and edge chipping. The tool rotation speed, work feed rate, power rating and abrasive size were selected as variable parameters. The results showed that the tool with helical grooved tool assisted the abrasives to replenish from machining zone, thereby reducing the WOC and edge chipping. Both very low and very high tool rotation speed, work feed rate, abrasive mesh size and low power rating resulted in lower WOC and edge chipping. The parametric combination of tool rotation speed 300 rpm, workpiece feed rate 20 mm/min, power rating 40% and abrasive mesh size #1200 resulted in lowest WOC and edge chipping and hence better form accuracy.

Keywords Micro-USM · Tool rotation · Micro-channel · WOC · Edge chipping

27.1 Introduction

Micro-channels are widely used in micro-fluidic devices and bio micro-electromechanical systems (MEMS) for mixing and analyzing the properties of fluid at micro scale [1]. The micro-fluidic devices are generally made from brittle materials such as glass and ceramic quartz. However, machining of these materials is either very difficult, time-consuming or very costly, specifically in micro-domain. The reason behind this is the superior properties of these materials such as high hardness, high strength and resistance to high temperature. In the past few years, several traditional and non-traditional manufacturing techniques have been used to develop micro-channels on these materials. These techniques include dry and wet etching, LIGA, electrochemical discharge machining, laser, micro-ultrasonic

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M. S. Shunmugam and M. Kanthababu (eds.), *Advances in Unconventional Machining and Composites*, Lecture Notes on Multidisciplinary Industrial Engineering, https://doi.org/10.1007/978-981-32-9471-4_27

machining (micro-USM), and so on. But all of these techniques have some limitations. Etching technique is limited to low aspect ratio micro-feature only [2]. LIGA requires an extremely clean environment and costly as well. ECDM and laser caused thermal damage to the work material [3]. Micro-ultrasonic machining (USM) is one of the mechanical-type non-traditional material removal process. It is used for the fabrication of micro-hole, micro-channels and other complex micro-features on hard and brittle materials, such as glass, quartz and ceramics [4]. Micro-USM does not modify the properties of the work material. Both conductive and non-conductive material can be easily machined by this process. In micro-USM, the material removal takes place from the work surface predominantly by the impact and hammering action of the abrasives in the form of tiny chips [5]. Some of the material is removed due to the erosion caused by the cavitation action and chemical reaction between abrasive slurry and the work material [6–8]. The limitations of this process are the low machining rate and high tool wear which hampered its use in many other applications. The literature revealed that the main cause of low machining rate and high tool wear in micro-USM is the debris accumulation in machining gap. In this process, the shape of the machined feature is decided by the tool shape. As the abrasive particle hits the tool, tool wear is inevitable in USM, which affects the dimensional accuracy of final machined cavity. Tool wear depends upon the tool material, shape and size of tool. Pei et al. in their investigation on micro-USM reported that the debris accumulation blocks the abrasive particles movement in the machining zone, which deteriorated the bottom surface of micro-hole [9]. Jain et al. [10] reported that in micro-USM, the relative contact between tool surface and machined cavity was responsible for the excessive tool wear. This deteriorates the form accuracy of machined feature. Cheema et al. [11] reported that higher power rating and higher slurry concentration deteriorated the surface finish and increased the tool wear also. Improper slurry circulation also leads to dimensional inaccuracy (in terms of overcut and edge chipping) of the machined micro-channels. Edge chipping becomes a serious issue where leakage is critical. Therefore, these issues also need to be addressed. In order to overcome the problem of debris accumulation and high tool wear, tool rotation was provided in the existing micro-USM process. This variant is known as rotary tool micro-USM (RTMUSM). The feasibility of RTMUSM to generate micro-features on glass was verified by Kumar and Dvivedi [12, 13]. They reported that the rotary motion of the tool assists the abrasives slurry to replenish from the machining gap. Tool wear also was reduced by providing the rotary motion to the tool. In another investigation, Kumar and Dvivedi [14] reported that desired dimensional accuracy of micro-channels can obtained by providing tool wear compensation. In order to further enhance the dimensional accuracy of rotary tool micro-USM, tool modification may be applied. Also, tool modification does not require any additional attachment on the existing setup. Therefore, in the present investigation, a helical grooved tool was selected for RTMUSM, and micro-channels were machined on borosilicate glass workpiece. The effect of RTMUSM parameters on the width overcut and edge chipping of micro-channels was analyzed. Further, the quality (in terms of form accuracy) of machined micro-channels was analyzed with the help of scanning electron microscope (SEM) images.

27.2 Materials and Methods

a. Experimental Setup

In this investigation self-developed facility of RTMUSM process, shown in Fig. 27.1, was used to fabricate micro-channels. The main components of RTMUSM setup are ultrasonic generator, rotary transducer, micro-tool, work feeding system and slurry feeding unit. The frequency of ultrasonic generator and maximum amplitude of vibration of the tool are 21 ± 1 kHz and 20 μm, respectively. The maximum tool rotation speed of 2500 rpm can be provided to the tool. The linear motion to the work material was provided with the help of X- and Y-axis table (resolution of 0.1 μm). The axes were controlled with the help of NC programming unit attached with the facility. Borosilicate glass, silicon carbide and high speed steel (HSS) were selected as work, abrasive and tool material, respectively. The tool along with machined micro-channel is shown in Fig. 27.2. The properties and chemical composition of work material is given in Table 27.1 [15, 16]. Tap water was used as liquid medium for slurry. The slurry was fed at a constant rate throughout the experimentation (Table 27.2).

b. Process Parameters

The experimentation was carried out by adopting one-factor-at-a-time approach taking tool rotation speed, power rating, feed rate and abrasive size as variable parameters. The WOC and edge chipping were selected as responses in this investigation. The values of variable and constant parameters are given in Table 27.3. The range of process parameters were selected on the basis of literature and successive experiments. Each experiment was conducted thrice and their average was taken as final response value. The WOC and edge chipping are schematically shown in Fig. 27.3.

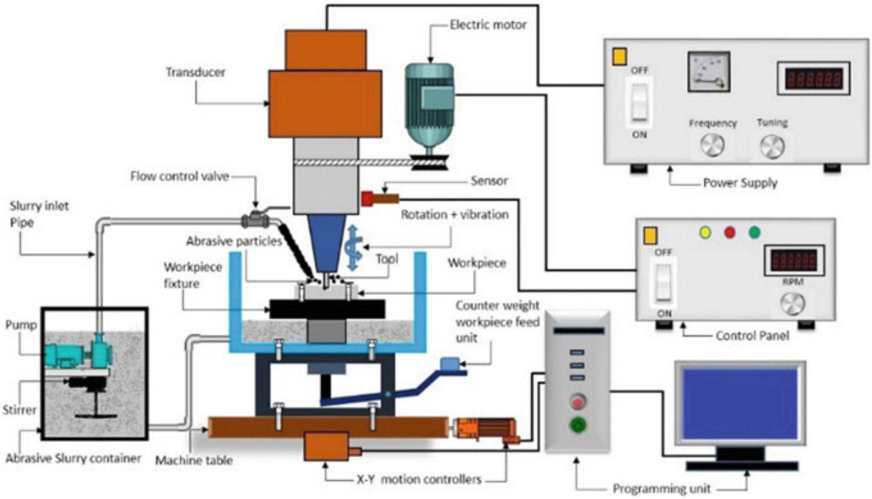


Fig. 27.1 Schematic of rotary tool micro-USM setup

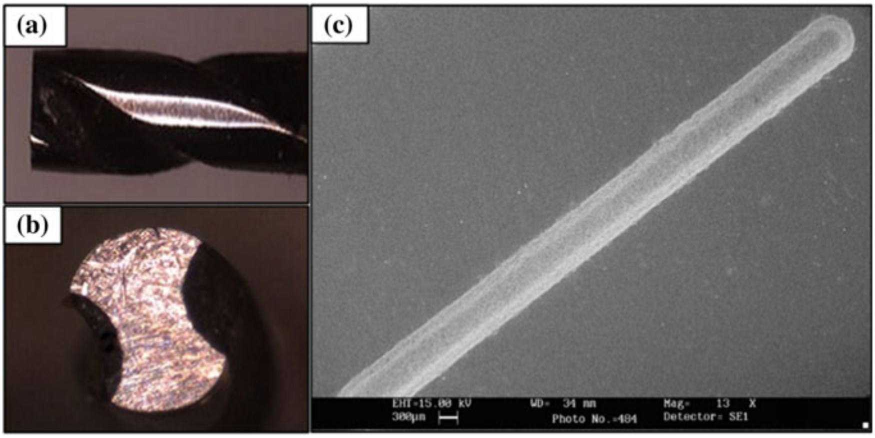


Fig. 27.2 **a**, **b** Front and top view of tool, **c** SEM image of machined micro-channel

Table 27.1 Chemical composition of borosilicate glass workpiece

Contents	S_iO_2	B_2O_3	$N_{a2}O + K_2O$	Al_2O_3	Mixed
% weight	80.6	13	4	2.4	0.1

Table 27.2 Properties of borosilicate glass workpiece material

Properties	Value
Coefficient of thermal expansion	32.5×10^{-7}cm/cm/°C
Density	2.23 g/cm^3
Melting point	821 °C
Glass transition temperature	525 °C
Poisson's ratio	0.2
Young's modulus	6.4×10^3 kg/mm^2

The WOC was measured using stereo zoom microscope (Make: NIKON, Model: SMZ-746T). The WOC was calculated using the formula given in Eq. 27.1. Edge chipping is the unwanted damage around the edges of the machined micro-channels (as shown in Fig. 27.3). Edge chipping was expressed in percentage and it was calculated using the formula given in Eq. 27.2.

$$WOC\ (\mu\text{m}) = (W_a - D_t) \tag{27.1}$$

where W_a and D_t are the actual width of micro-channel and tool diameter, respectively.

Table 27.3 Process parameters and their values

S. no.	Parameter	Value
1	Rotational speed (rpm)	100–700
2	Work feed rate (mm/min)	10–25
3	Power rating (%)	10–60
4	Abrasive size (mesh)	#800–#1800
5	Frequency (kHz)	21 ± 1
6	Slurry concentration (%)	20
7	Liquid medium	Water
8	Tool diameter (μm)	850
9	Static load (g)	45
10	Tool material	HSS
11	Workpiece material	Borosilicate glass
12	Abrasive material	Silicon carbide

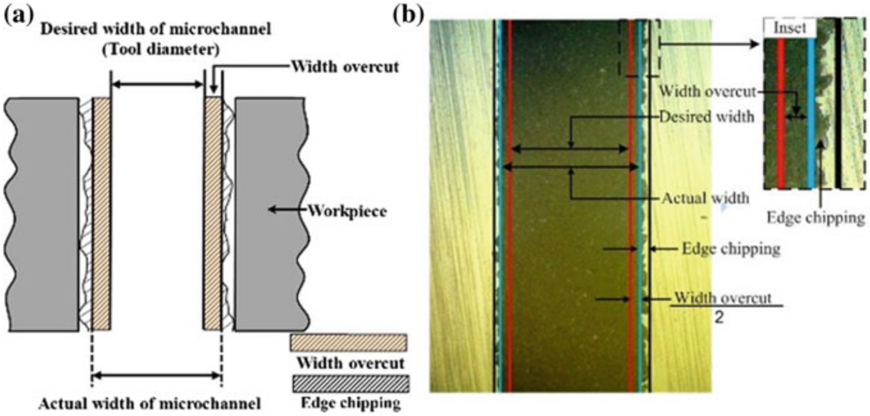


Fig. 27.3 **a** Schematic of WOC, **b** top view of machined micro-channel

$$Edge\ chipping\ (\%) = \frac{(V_t - V_d)}{V_d} \times 100 \tag{27.2}$$

where V_t and V_d are the total volume and desired volume of material removed, respectively.

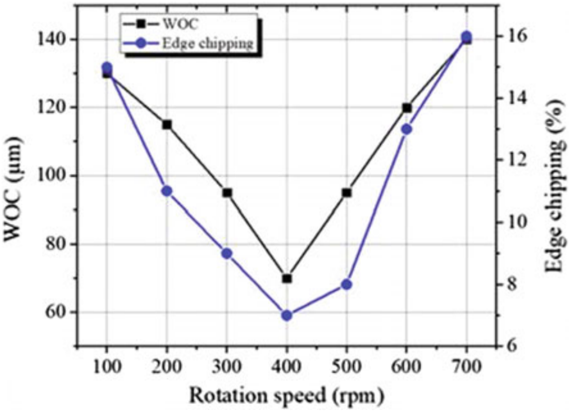
27.3 Discussion of Experimental Results

27.3.1 Process Parameters Effect on WOC and Edge Chipping

The effect of tool rotation speed on WOC is presented in Fig. 27.4. From Fig. 27.4, it can be clearly seen that as the rotation speed increased from 100 to 400 rpm, both the WOC and edge chipping reduced. Beyond 400 rpm an increasing trend was observed in both WOC and edge chipping. The reason attributed to the observed trend was that rotary motion of tool exerted centrifugal force on abrasive slurry. The centrifugal force eases the circulation of abrasives in the machining zone. On increasing the tool rotation speed, centrifugal force on abrasive slurry was increased, leading to faster slurry replenishment. In addition, the helical groove provided extra space to the abrasives slurry to enter and exit from machining zone (as shown in Fig. 27.5). As a result of that, WOC and edge chipping reduced. The minimum WOC and edge chipping were achieved at 400 rpm. Also, the tool rotation speed of 400 rpm resulted in maximum depth and better form accuracy of micro-channel (Fig. 27.6a). This implies that tool rotation speed of 400 rpm was sufficient for effective circulation of slurry. Beyond 400 rpm, excessive centrifugal force applied on the slurry due to which the abrasives present in the slurry stroked on the edges and side wall of the machined micro-channel. Consequently, WOC and edge chipping increased.

The effect of feed rate on WOC and edge chipping is presented in Fig. 27.7. It was observed that the WOC and edge chipping initially decreased up to 20 mm/min of feed rate and after that both started to increase (Fig. 27.7). It is believed that the feed rate governs the time of interaction between abrasive, tool and work material. At lower feed rate, interaction time was more due to which abrasives contributed to machining for longer period of time and higher WOC and edge chipping were obtained. On the other hand, at very high feed rate (i.e. beyond 20 mm/min), interaction time between tool, abrasives and work material significantly reduced due to which lesser

Fig. 27.4 Rotation speed effect on WOC and edge chipping



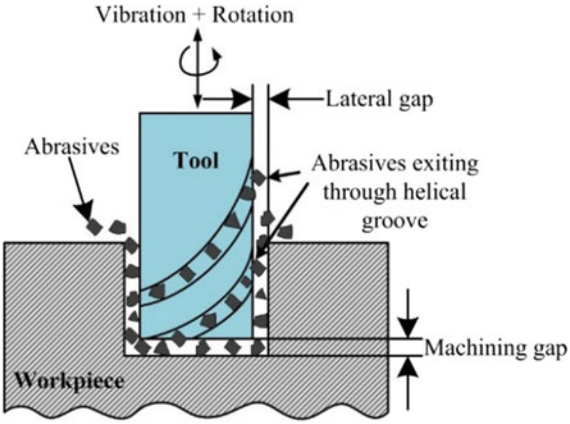
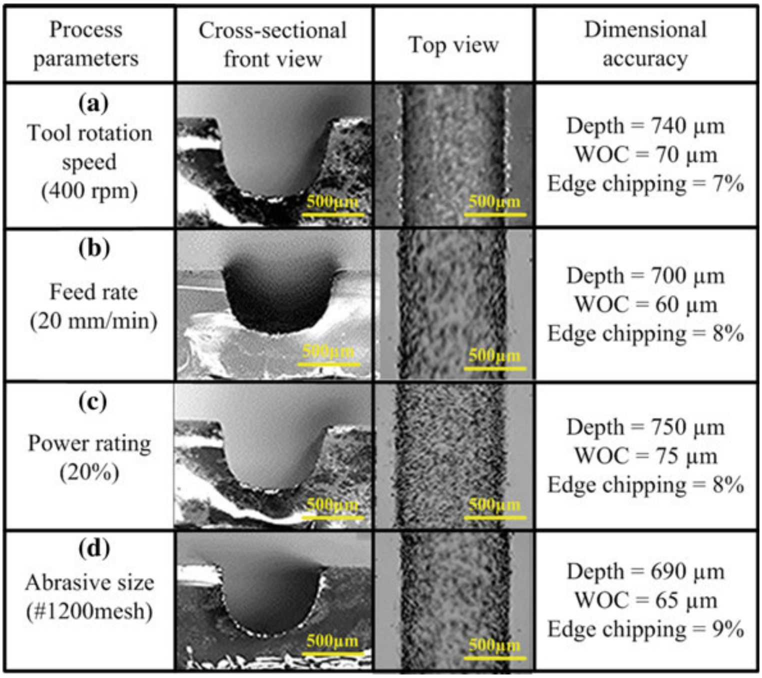


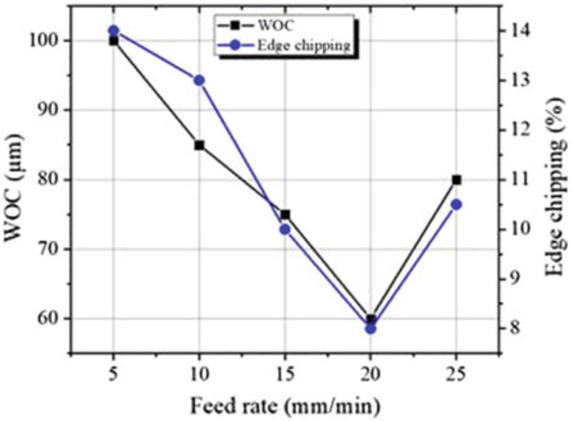
Fig. 27.5 Schematic representation showing abrasive replenishment through helical grooves



Process parameters	Cross-sectional front view	Top view	Dimensional accuracy
(a) Tool rotation speed (400 rpm)			Depth = 740 µm WOC = 70 µm Edge chipping = 7%
(b) Feed rate (20 mm/min)			Depth = 700 µm WOC = 60 µm Edge chipping = 8%
(c) Power rating (20%)			Depth = 750 µm WOC = 75 µm Edge chipping = 8%
(d) Abrasive size (#1200mesh)			Depth = 690 µm WOC = 65 µm Edge chipping = 9%

Fig. 27.6 Cross-sectional and top view of machined micro-channels

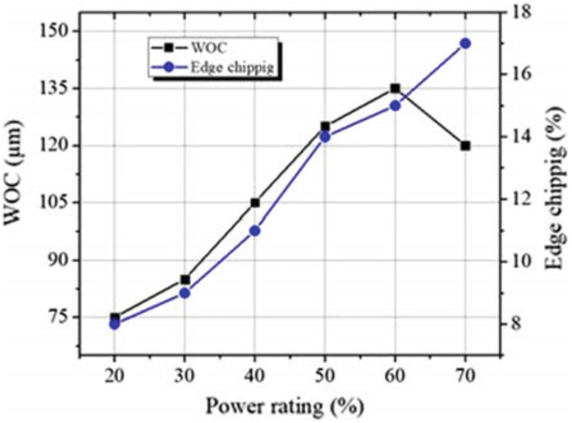
Fig. 27.7 Feed rate effect on WOC and edge chipping



quantity of abrasives took part in machining. Moreover, there might be a direct contact between tool and work material causing damage to sidewall of micro-channel. Consequently, higher WOC and edge chipping were observed. The feed rate of 20 mm/min was found to be sufficient for tool abrasive and workpiece interaction. The maximum depth of micro-channel and good form accuracy were obtained at 20 mm/min (Fig. 27.6b).

The power rating is directly related to the impact energy imparted by the tool to the work surface via abrasive particles. Power rating has a linear relation with the amplitude of vibration. Figure 27.8 illustrates the effect of power rating on WOC and edge chipping. From Fig. 27.8, it can be observed that on increasing power rating, the WOC and edge chipping were found to be increased. At power rating of 20%, both the WOC and edge chipping were low due to lesser impact energy transfer to abrasive particles on work surface. On increasing the power rating from 20 to 70%, the impact energy significantly increased and deep crater was created by the

Fig. 27.8 Power rating effect on WOC and edge chipping



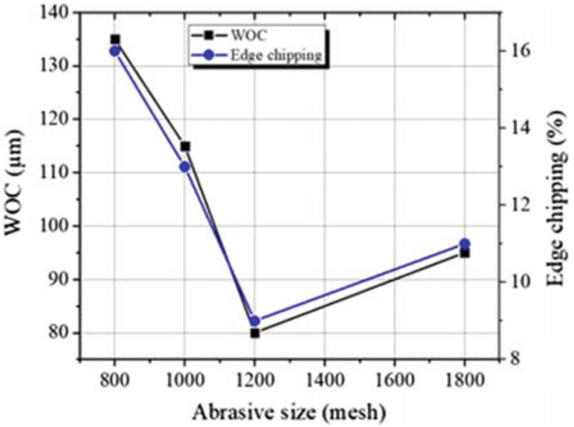


Fig. 27.9 Abrasive size effect on WOC and edge chipping

impact of abrasives. Thus, WOC and edge chipping increased. The form accuracy of micro-channel at 20% of power rating was found to be better (Fig. 27.6c).

The size of abrasive particle greatly affects the performance of micro-USM because in USM, the width of the machined cavity is defined as the sum of tool diameter and twice of the abrasive particle size [4]. The abrasive mesh size has inverse relation with average grain diameter of abrasive particle. The effect of abrasive mesh size on the WOC and edge chipping is presented in Fig. 27.9. From Fig. 27.9, it can be seen that on increasing the abrasive size from #800 mesh to #1200 mesh, both the WOC and edge chipping decreased. The average grain diameter of abrasive particles reduced by increasing the mesh size, due to which the lateral gap (the gap between the side wall of cavity and tool surface) decreased. Thus, low WOC was obtained. The damage at the edges of the micro-channels was also reduced due to the smaller grain diameter of abrasives. On further increasing the abrasive mesh size from #1200 mesh to #1800 mesh, the average grain diameter significantly reduced. This caused the formation of multiple abrasives layers in machining gap. The multiple layers of abrasives when exited through the lateral gap increased the WOC and edge chipping. The form accuracy of the micro-channels was better when #1200 mesh size abrasive particles were used (Fig. 27.6d). This implies that a uniform layer of abrasive particles circulated while using #1200 mesh size abrasives.

27.4 Conclusions

In the current investigation, the effectiveness of tool with helical groove in rotary tool micro-USM was evaluated. Experiments were conducted on borosilicate glass work material as per OFAT approach. The RTMUSM parameters, namely tool rotation speed, feed rate, power rating and abrasive size, varied and the performance was evaluated in terms of WOC and edge chipping. The conclusions drawn from this investigation are summarized as follows:

- The helical grooved tool was found to be an effective solution for abrasive replenishment in RTMUSM.
- Micro-channels were developed on glass using helical grooved tool in RTMUSM.
- For an increase in tool rotation speed, feed rate and abrasive size, the WOC and edge chipping initially decreased and after that both increased.
- By increasing power rating, the WOC and edge chipping were found to increase.
- The lowest WOC and edge chipping were observed at rotation speed = 400 rpm, work feed rate = 20 mm/min, power rating = 20% and abrasive size = 1200 mesh, respectively.
- Further, there is a need to optimize the process parameters of rotary tool micro-USM using helical grooved tool to achieve the minimum WOC and edge chipping simultaneously.

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