Experimental investigations in development of 3D microchannels through ultrasonic micromachining

Manjot Singh Cheema[1#], Akshay Dvivedi[1], Apurbba Kumar Sharma[1] and Sourav Acharya[1]
1 Department of Mechanical and Industrial Engineering, Indian Institute of Technology, Roorkee-247667, India
Corresponding Author / E-mail: manjotcheema@hotmail.com, TEL: +917409128713,

KEYWORDS : Ultrasonic micromachining , 3 D microchannels

3D microchannels proved to be beneficial for mixing two or more fluids at micro levels. Ultrasonic micromachining is a cost effective solution to fabricate micro features on hard and brittle surfaces. This study discusses the effect of abrasive concentration, power rating and workpiece feed on development of 3D microchannel on borosilicate glass. The output parameters studied were surface roughness and tool wear. It was found that increase in power ratings and abrasive concentration lead to deterioration of surface finish and increased tool wear. But at high workpiece feed rates, the surface finish improved and the tool wear decreased. Tungsten carbide was used as the tool material.

NOMENCLATURE

3 D = Three dimensional
PDMS = Poly diomethyl siloxane
EDM = Electric discharge machining
LBM = Laser Beam Machining
USMM= Ultrasonic micromachining

1. Introduction

The ability to fabricate complex structures and patterns at micron and nano level has facilitated use of many miniature devices in various applications. Fluid mixing is one of the major requirements in such microfluidic devices [1]. Efficient mixing of two and more fluids was made possible by development of 3 D microchannels [2, 3]. Effective mixing was observed due to chaotic advection. Further, such systems were also used in providing 3 D environment for cell growth [4]. As fabrication of 3 D microchannels was concerned, poly dimethyl siloxane (PDMS) was reported as the easiest material to fabricate microchannels using molding techniques [5,6]. Moreover, wet etching technique was also used for fabricating 3D microchannel in silicon wafer [3]. A lithographic method was used initially to fabricate microchannel in a photoresist, the different layer of microchannels were combined by special adhesive bonding to develop a 3 D array in a later stage [7]. Femto second micromachining was another technique for development of complex geometries in silicon [8].

A number of methods are available for micromachining depending upon the application area. But these micromachining methods involve a number of complexities. Lithography and bulk micromachining are promising techniques but there are highly expansive and demand clean room facilities [9]. Micro EDM can only be used for conductive materials and LBM leads to heat affected zones. Soft lithography is used for polymeric materials like PDMS that cannot resist high temperatures [10]. Moreover, conventional machining techniques involve tool fabrication complexities.

USMM becomes an affordable solution in this scenario where a compromise between process economics and machining quality is to be done. It is a promising solution for machining of hard and brittle materials. The flexibility to machine 3 D complex geometries has been reported by several researchers [11, 12]. This paper presents a study on fabrication of 3 D stepped microchannel. Power rating, abrasive concentration and feed rate were considered as the process parameters to study the observed surface roughness and tool wear in different microchannels.

2. Setup fabrication and experimental details

A layer-by-layer machining approach was used to fabricate a 10 mm long microchannel which consisted of two steps. Both the steps were 5 mm long with intended depth to be achieved for first step of the microchannel be 170 µm and the other step be 340 µm. A fixed increment of 10 µm was given to the tool in Z axis (step feed). The various process parameters used in this study are shown in Table 1. A one factor approach at a time was used to study the effect of different process parameters. The experiments were done more than two times and the averages were taken. Tool wear was measured with the help of a tool maker's microscope (Nikon MM 200). The surface roughness was measured with the help of a surface roughness tester (Mitutoyo SJ 400). The microchannel developed by this method at 70 % power rating and a feed of 20 mm/min is shown in Figure 1.

Table 1. Parameters of the USMM

Experimental conditions	
Power	800 W
Vibration frequency	21 kHz
Abrasive material	Silicon carbide
Abrasive size (mesh size)	1000
Workpiece material	Borosilicate glass
Tool Material	Tungsten Carbide
Tool Diameter	Ø 600 µm
Feed in X direction	10, 20, 30 mm/min
Feed in Z direction	10 µm
Total depth given in Z direction	170 µm - first step, 340 µm- second step
Slurry concentration	15%, 20%, 25%, 30% abrasive by weight
Slurry medium	Water
Power rating	90%, 80%, 70%, 60%

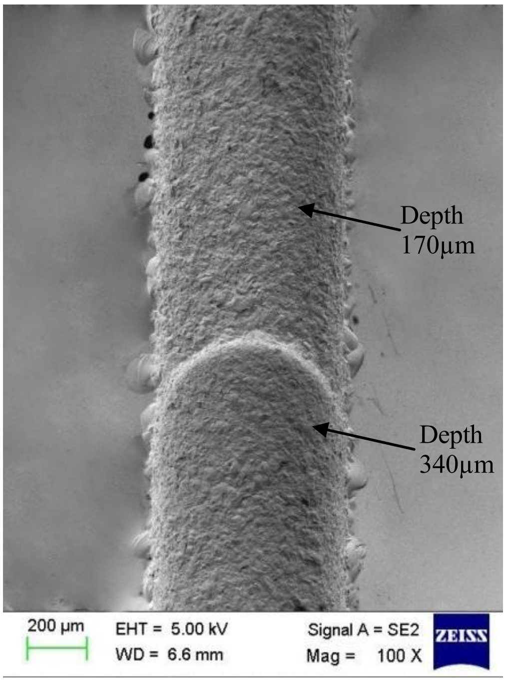
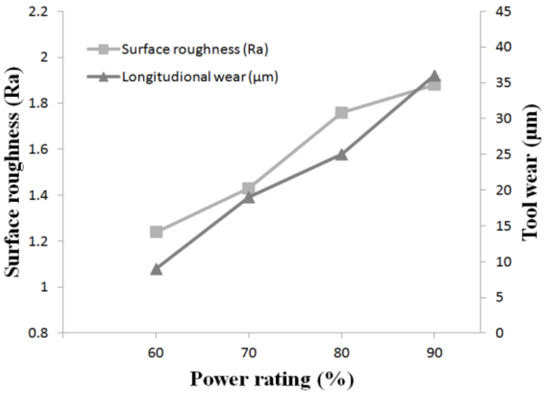


Fig. 1 Top view of stepped microchannel developed through USMM

2.1 Effect of power rating

Power rating decides the energy with which abrasive particle strikes the workpiece surface. Higher power ratings result in abrasive particles striking with higher energy. This energy induces greater damage by indenting inside the workpiece and forming large sized craters. With a decrease in power rating an improvement in surface finish was observed as shown in Figure 2. The size of the craters formed on lower power rating decreases resulting in better surface finish. Similarly the reduction in tool length due to wear (longitudinal wear) was observed to be more at higher power ratings as shown in Figure 2. Repetitive impacts of abrasives on tool lead to formation of micro pits that act as a site of failure after some time. High power ratings lead to tool striking abrasives with higher impacts. The abrasive particles indent inside the tool face resulting in formation of micro pits and act as a site for crack propagation.

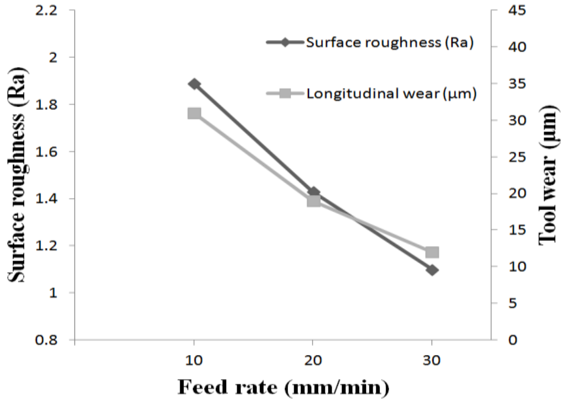


Feed rate - 20 mm/min, Abrasive concentration 20 %

Fig.2 Effect of power rating on surface roughness and longitudinal wear

2.2 Effect of feed

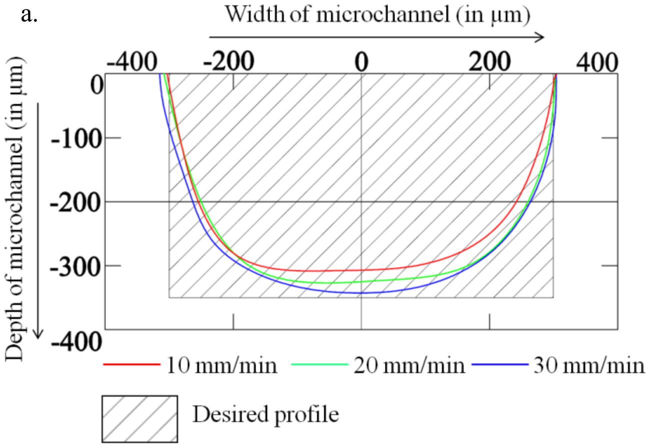
Feed can be defined as the relative motion between the tool and workpiece with respect to time. In this case, the workpiece was given a feed of 10, 20 and 30 mm/min. Feed rate decided the interaction time between tool abrasives and workpiece. More the interaction time, more are the impacts suffered by the tool. More the number of impacts, higher was the longitudinal wear observed as shown in Figure 3. The developed profiles for both the half's of microchannel are shown in Figure 4 (a) & (b). The microchannel depth increased with increase in feed, the effect of tool wear is directly reflected on the depth of the microchannel. At a feed rate of 10 mm/min the tool wear was more, thus the depth obtained in both the half's of microchannel reflected deviation from intended depth of the microchannel (Figure 4 (a) & (b)). Moreover, the walls of the microchannel are slightly tapered and no sharp edges were observed due to abrasive action



Power rating - 70 %, Abrasive concentration - 20 %

Fig.3 Effect of feed rate on surface roughness and longitudinal wear

a.



b.

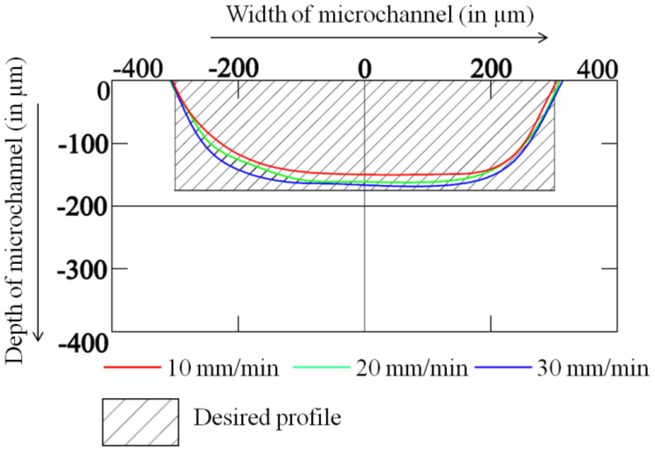
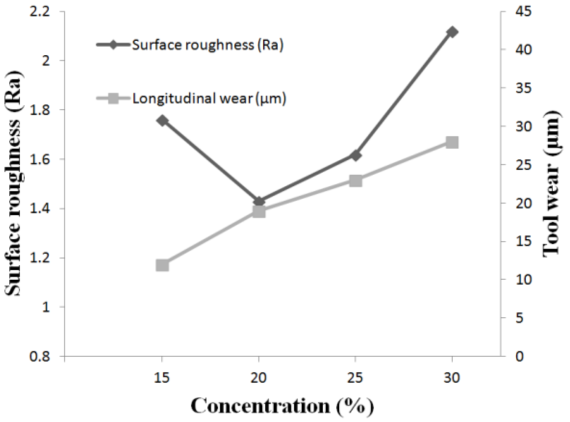


Fig. 4(a) Microchannel profile developed at different feed rates for desired depth of 340 µm

Fig. 4(b) Microchannel profile developed at different feed rates for desired depth of 170 µm

2.3 Effect of concentration

Abrasive concentration is an important surface finish deciding factor. The best surface finish was obtained at a concentration of 20 % by weight as shown in Figure 5. However, with increase in abrasive concentration, increase in longitudinal wear was also observed. This can be accounted due to the reason that more abrasive particles come in contact with the tool face leading to increased number of impacts. The increased interaction of the abrasives with the tool is responsible for longitudinal wear as shown in Figure 5.

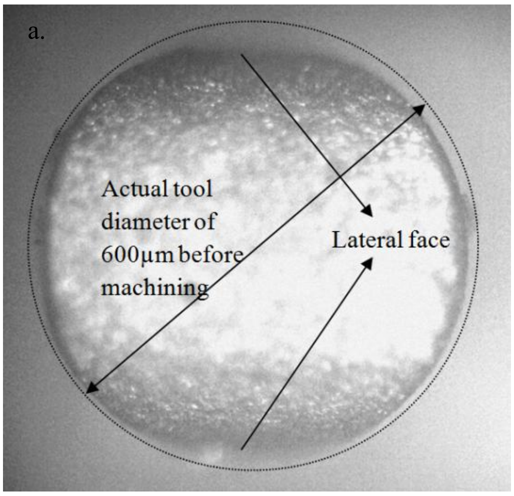


Power rating - 70 %, Feed - 20 mm/min

Fig. 5 Effect of concentration level on surface roughness and longitudinal wear

3. Tool wear

Tool wear is an important aspect that decides the form accuracy of the microchannel. USMM is one such method where the tool shape is replicated on the workpiece. However, from Figure 4 (a) & (b) it can be seen that slight variation is observed in the from accuracy. Tapered walls and rounded edges can be seen at different feed rates. This phenomenon can be explained on the basis of observed tool wear on the face and the sides as shown in Figure 6 (a) & (b), the tool wear can be classified into following types - edge rounding wear, lateral face wear and longitudinal wear. Longitudinal wear leads to reduction in length. Edge rounding wear leads to reduction in diameter and lateral face wear leads to flat faces over the sides as shown in Figure 6 (b). Longitudinal wear occurs due to direct impact of abrasive particles on the tool face. Edge rounding occurs when the abrasive particle escape from the working gap to the lateral gap, this results in rubbing the edges of the tool. Lateral face wear occurred when abrasive particle gets trapped between the workpiece walls and the tool walls. The lateral face wear is highly dependent upon the contour to be developed. Two different profiles, the L slot and T slot are shown in Figure 7 (a) & (b). Tools used in development of such profiles have multiple lateral faces depending upon the contour shape.



b.

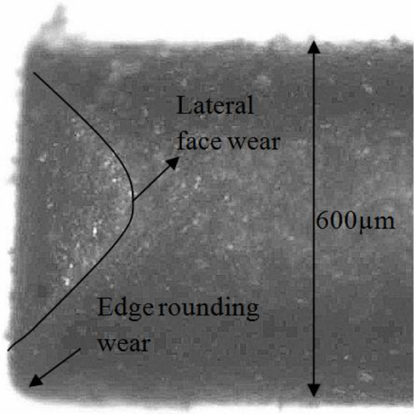
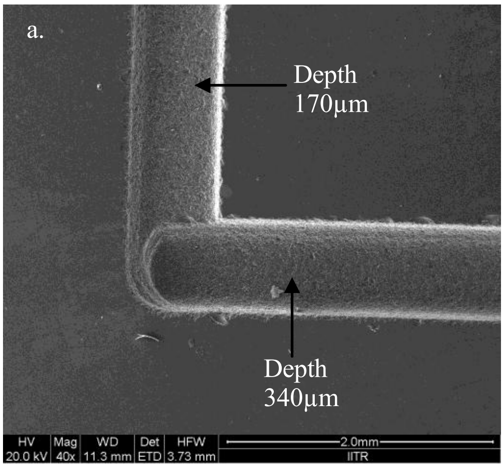


Fig. 6(a) Microscopic image showing face of the tool.

Fig. 6(b) Microscopic image showing side view of the tool



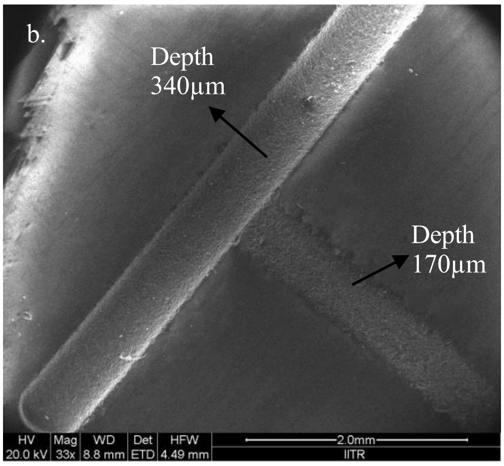


Fig. 7(a) SEM image of the L slot

Fig. 7(b) SEM image of the T slot

4. Scope for future work

Surface finish can be improved drastically by using the appropriate abrasive size and power rating. Moreover, with such settings, the tool wear and the stray cutting can also be minimized. Further, bonding of such microchannel to develop a closed 3D microchannel is another area where work can be done.

5. Conclusions

The following conclusions can be drawn from the study

1. USMM possesses the flexibility to develop complex and intricate 3D shapes.
2. Tool wear reduced and surface finish improved at higher feed rates.
3. An optimum level of 20 % concentration yields the best surface finish.
4. Power rating played a prominent role in deciding the tool wear and the surface finish. Tool wear reduced and surface finish improved at lower power ratings.

ACKNOWLEDGEMENT

The authors are gratefully acknowledge financial support from Department of Science and Technology (DST), India, Grant no. SB/FTP/ETA/207/2012.

REFERENCES

1. Nguyen, N. T. and Wu, Z., "Micromixers—a review," Journal of Micromechanics and Microengineering, Vol. 15, No. 2, pp. R1–R16, 2005
2. Ng, J. M. K., Gitlin, I., Stroock, A. D. and Whitesides, G. M., "Components for integrated poly(dimethylsiloxane) microfluidic systems," Electrophoresis, Vol. 23, pp. 3461–3473, 2002.
3. Liu, R. H., Stremler, M. A., Sharp, K. V., Olsen, M. G., Santiago, J. G., Adrian, R. J., Aref, H. and Beebe, D. J., "Passive Mixing in a Three-Dimensional Serpentine Microchannel," Journal of Microelectromechanical Systems, Vol. 9, pp.190-197, 2000
4. Jo, B. H., Van Lerberghe, L. M., Motsegood, K. M. and Beebe, D.J., "Three-dimensional micro-channel fabrication in polydimethylsiloxane (PDMS) elastomer," Journal of Microelectromechanical Systems, Vol. 9, No.1, pp. 76—81, 2000.
5. Bauer, M., Su, G., Beebe, D. J., and Friedl, A., "3D microchannel co-culture: method and biological validation," Integrative Biology, Vol. 2, pp. 371-378, 2010.
6. Jia, Y.F., Jiang, J.H., Ma, X.D., Li, Y., Huang, H.M., Cai, K.B., Cai, S.X. and Wu, Y.P., "PDMS microchannel fabrication technology based on microwire-molding", Chinese Science Bulletin, Vol. 53, No. 24, pp. 3928–3936, 2008.
7. Blanco,F. J., Agirregabiria, M., Garcia, J., Berganzo, J., Tijero, M., Arroyo, M. T., Ruano, J. M., Aramburu, I. and Mayora, K., "Novel three-dimensional embedded SU-8 microchannels fabricated using a low temperature full wafer adhesive bonding," Journal of Micromechanics and Microengineering, Vol. 14, pp. 1047–1056, 2004.
8. Li, C., Chen, T., Si, J., Chen, F., Shi, X., and Hou, X., "Fabrication of three-dimensional microchannels inside silicon using a femtosecond laser," Journal of Micromechanics and Microengineering Vol. 19, pp. 125007, 2009.
9. Jáuregui, A. L., Siller, H. R., Rodríguez, C. A. and Elías-Zúñiga, A., "Evaluation of micromechanical manufacturing processes for microfluidic devices", International journal of Advance Manufacturing Technology, Vol. 48, pp. 963–972, 2010.
10. Ziaie, B., Baldi, A., Lei, M., Gu, Y. and Siegel, R. A., "Hard and soft micromachining for BioMEMS: Review of techniques and examples of applications in microfluidics and drug delivery", Advanced Drug Delivery Reviews, Vol. 56, No. 2, pp. 145 -172, 2004.
11. Yu, Z., Rajurkar, K. P. and Tandon, A., "Study of 3D Micro Ultrasonic Machining", ASME Journal of Manufacturing Science and Engineering, Vol. 126, No. 4, pp. 727-732, 2004.
12. Sun, X.Q., Masuzawa, T., and Fujino, M., "Micro Ultrasonic Machining and Self-Aligned Multilayer Machining/Assembly Technologies for 3D Micromachines", Proceedings of Ninth Annual International Workshop on Micro ElectroMechanical Systems (MEMS'96), pp. 312-317, 1996.