

Fabrication of μ -Channels on Pure-Ti using USM and Optimization of Process Parameters



Rahul Dev Gupta, Pardeep Gupta

Abstract: Today, the appropriate use of precision machining to produce three dimensional miniaturized structures or micro devices is another challenging task. Thus, presently miniaturization has emerged as a thrust area of research. The micro components are normally provided with micro channels which are created by using micro tools with the help of nonconventional machining processes. The aim of this paper is to examine machining performance of making micro channels in pure-Ti using ultrasonic machining. The effect of abrasive type, power rating, slurry concentration, feed rate and abrasive size has been investigated on responses namely metal removal rate (MRR) and surface roughness (SR). Taguchi based L_{18} (mixed level) orthogonal array is selected for the planning of experiments. Finally, the validation experiments have been performed at suggested optimal settings for result reproducibility.

Keywords: Micro Channels, Pure Ti, Ultrasonic Machining, Taguchi

I. INTRODUCTION

A microchannel may be defined as a via to move fluid from one part of a microchip to another part. Microchannels are typically made of silicon, glass, metals like Titanium, Copper, Stainless Steel and often feature circular, rectangular or trapezoidal cross sections, ranging in terms of the hydraulic diameter from 1 μm to 1000 μm . The sole purpose of the microchannels is either to extract the heat from a hot body through flowing fluid or to precisely control and manipulate a fluid sample movement at micron scale. Microchannels are currently being used in many areas and have high potential for applications in many other areas, which are considered realistic by experts. The application areas include medicine, biotechnology, avionics, consumer electronics, telecommunications, metrology, computer technology, office equipment and home appliances, safety technology, process engineering, robotics, automotive engineering and environmental protection. Devices such as hard disk drive heads, inkjet print heads, heart pacemakers, pressure and chemical sensors, drug delivery systems, infrared imagers, micromotors,

microchannel reactors, micropumps & turbines and microchannel heat sinks are just a few among the large number of microdevices being commercially used or will be used in the near future. Now the scientists have begun to explore and investigate some other novel non-conventional fabrication techniques for the production of micro channels instead of using the traditional micro fabrication methods.

Ultrasonic Micro Machining (micro USM) seems to be a good alternative for the production of micro channels because being a non-electrical, chemical and thermal process does not significantly change any of the properties of work-piece material. Ultrasonic Micro Machining has a set of control variables similar to macro-USM, abrasive particles of micro size, a micro sized tool, and smaller amplitude of vibration. In this the tool vibrates with amplitude of few micrometers. The abrasive slurry is supplied into the gap between work piece and the tool. Once the vibrating tool strikes to the free abrasive particles, they attain some momentum and force the target work-piece. Material is removed by the continuous impact and micro-chipping. Further, cavitation can play a key role in material removal at micro-level. Water is normally preferred as the slurry medium and a continuous flow of slurry will ensure that debris are being flushed away from the machining zone and the gap is filled with fresh slurry.

Elisa et al. (2011) fabricated arrays of microchannels on aluminium and titanium plates, by using micro milling. Darvishi et al. (2012) fabricated tapered microchannels in hard and soft transparent solid (PDMS elastomer), by ultrafast laser machining with wavelength of 800 nm. Pang et al. (2012) found abrasive water jet technology as an attractive feasibility to produce complex shapes on difficult – to – cut materials as well as exotic materials without inducing thermal effects. Ciurana et al. (2012) analysed the relationship between geometrical features of the micro-part and variation of process parameters. Micro part was fabricated using, titanium (Ti6Al4V) & stainless steel (316L), with hardness of 107 HRB and 88 HRB respectively. Sun et al. (1996) made the first attempt of downsizing macro USM for micromachining in mid-1990's. Kumar and Kumar (2011) discussed that USM could be a viable alternative for processing of pure titanium (ASTM Grade-I). The optimal settings of parameters were determined and tool wear rate (TWR) was evaluated under controlled experimental conditions. Jain et al. (2011) presented the latest research done and future areas for micro-USM. Developments in the critical areas of the process like precision attainable, transducers, machining tool head and machine tool technology. Khanna and Singh (2014) calculated grey relational coefficients and grey relational grade, using Grey relational analysis. Significant factors for multi-response optimization were found out by ANOVA.

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Sharma et al. (2015) utilized an integrated approach of entropy measurement method, grey relational analysis and Taguchi method for obtaining optimum settings of process parameters. Singh & Singhal (2016) experimentally investigated the influence of ultrasonic power, coolant pressure, spindle speed and feed rate on surface roughness, and chipping thickness. Experiments were designed using Response surface methodology. Shaolin et al. (2017) reviewed the existing ultrasonic-assisted machining literature along with the rotary ultrasonic texturing (RUT) technology.

A detailed literature review indicates that USM has the capability for precision micromachining of various materials. Moreover, there is a lack of work on micro-channel fabrication in soft and hard materials for various applications by advanced processes especially USM. Furthermore, fabrications of micro-channels in a single run in USM and its parametric optimization for machinability enhancement have also been worked out limitedly. The micro-channels are being widely used commercially in various scientific, industrial, and precision applications; it necessitates exploring advanced machining processes such

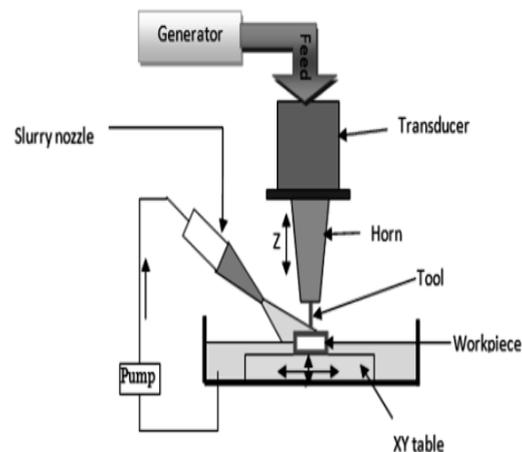
as USM to fabricate precision micro-channels, hence, the feasibility of fabricating the μ -channels on ductile materials like titanium using advance machining processes such as ultrasonic μ -machining has been explored in the present work. Further, the comparison of optimized results, obtained by GRA and NSGA-II for the fabrication of μ -channels on Pure-Ti using USM has also been done to find out that from which method the predicted results obtained are better.

II. EXPERIMENTATION & MEASUREMENT

Sonic mill (USA, AP-500) make USM (Fig. 1a) has been used for the machining of commercially pure Titanium grade 2. Fig. 1 (b) represents the schematic diagram of the ultrasonic machining (USM) and actual picture of the USM machine tool used in the present research. In USM, electrical energy generated is converted in mechanical vibrations with the help of transducer and based upon the principle of resonance; maximum vibration amplitude can be generated. Abrasive slurry is supplied into the tool-workpiece gap. The shape of tool remains the replica of the shape required to be generated in the work-material.



(a)



(b)

Fig. 1 (a) Machine tool used in present work (b) Schematic representation of USM

A micro-tool of stainless steel has been developed in the present work for micro-channels machining. Five numbers of stainless-steel strips are cold brazed on the bolt, which is further connected to the tool holder. The cold brazing is

used to avoid any chance of steel strips melting. Fig. 2 represents the development of micro tool and top and side view of the developed micro-tool used for micro machining purpose in the present research.

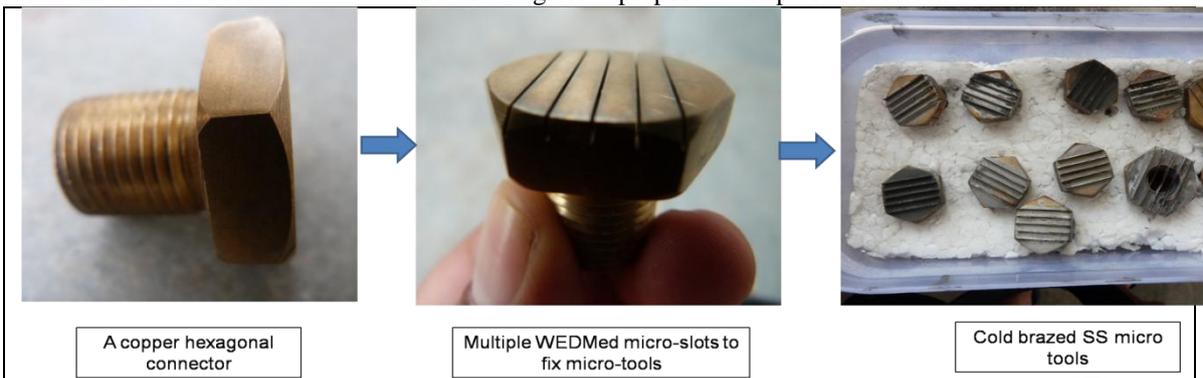


Fig. 2

Table 1 shows the chemical composition of Titanium material used in the present work. Material removal rate (MRR) which represents the process productivity has been calculated by weight loss method and the average surface

roughness of the machined samples is measured with the help of Atomic Force Microscope (AFM). For each microchannel, three readings of surface roughness were taken and average value of roughness was considered.

Table 1: Chemical Composition of Titanium grade-2 used in the present work

Element	Percentage (in %wt.)
Carbon	0.06
Oxygen	0.2
Nitrogen	0.025
Iron	0.25
Hydrogen	0.013
Titanium	Remaining

Table 2 Details of USM parameters used in the present work

Sr. No	Control variables	Designation	No of Levels	Levels		
				Level 1	Level 2	Level 3
1	Abrasive Type	A	2	SiC	B ₄ C	----
2	Power Rating (machine units)	B	3	20	30	40
3	Slurry Concentration (%)	C	3	10	20	30
4	Feed Rate (mm/min)	D	3	0.05	0.1	0.2
5	Abrasive Size (µm)	E	3	1	5	10

III. RESULTS AND DISCUSSION

Table 3 presents the eighteen experimental combinations and corresponding values of responses. A detailed analysis

about the effect of USM parameters on both response parameters is given here as under.

Table 3 Experimental combinations of process parameters and corresponding responses

Sr. No.	AT	PR	SC	FR	AS	MRR1	MRR2	MRR3	MRR (S/N)	SR1	SR2	SR3	SR (S/N)
1	SiC	20	10	0.05	1	0.0515	0.0537	0.052	-25.618	0.38	0.39	0.4	8.163
2	SiC	20	20	0.1	5	0.0623	0.0645	0.07	-23.693	0.41	0.45	0.53	6.595
3	SiC	20	30	0.2	10	0.098	0.0808	0.102	-20.712	0.75	0.73	0.73	2.622
4	SiC	30	10	0.05	5	0.0935	0.102	0.0996	-20.161	0.53	0.63	0.53	4.954
5	SiC	30	20	0.1	10	0.1253	0.1135	0.1153	-18.584	0.92	0.93	0.93	0.674
6	SiC	30	30	0.2	1	0.253	0.267	0.2673	-11.628	0.53	0.57	0.58	5.037
7	SiC	40	10	0.1	1	0.0916	0.0816	0.0968	-20.982	0.69	0.69	0.69	3.248
8	SiC	40	20	0.2	5	0.032	0.0667	0.0845	-26.504	0.78	0.78	0.78	2.147
9	SiC	40	30	0.05	10	0.0502	0.0702	0.0902	-23.818	0.98	1	0.92	0.287
10	B ₄ C	20	10	0.2	10	0.165	0.168	0.172	-15.480	1.87	1.2	1.94	-4.622
11	B ₄ C	20	20	0.05	1	0.172	0.192	0.1972	-14.606	1.82	1.94	2.1	-5.823
12	B ₄ C	20	30	0.1	5	0.278	0.276	0.288	-11.041	1.63	1.73	1.72	-4.587

13	B ₄ C	30	10	0.1	10	0.1987	0.1992	0.1993	-14.020	2.11	2.22	2.24	-6.812
14	B ₄ C	30	20	0.2	1	0.1923	0.1945	0.1984	-14.199	1.83	1.95	1.83	-5.436
15	B ₄ C	30	30	0.05	5	0.226	0.256	0.266	-12.128	1.58	1.99	1.75	-5.011
16	B ₄ C	40	10	0.2	5	0.1734	0.1735	0.1723	-15.236	0.65	0.75	0.73	2.918
17	B ₄ C	40	20	0.05	10	0.078	0.08	0.0748	-22.213	1.58	1.55	1.65	-4.048
18	B ₄ C	40	30	0.1	1	0.212	0.201	0.214	-13.607	1.23	1.43	1.24	-2.301

*AT-Abrasive type, PR-Power rating, SC-Slurry concentration, FR-Feed Rate, AS-Abrasive size

A. Influence of USM parameters on MRR

Fig. 4 shows the variation of MRR means with all USM parameters considered. It is found that with increase in PR from 20 μ to 30 μ , MRR increases, and then decreases with further increase in PR from 30 μ to 40 μ . A large value of power rating enhances the rate of machining due to increase in the momentum by which the abrasive particles strike the work surface. MRR decreases when the SC increases from 0% to 20%, and its value increases with further increase in SC from 20% to 30%. Increase in slurry concentration implies, more abrasive particles involved in cutting, which increase MRR. Further increase in concentration, abrasive slurry squeezes the movement of the tool, as a result of abrasive particles collide with each other causing loss of cutting energy and thus results in decrease in MRR. MRR increases by increasing feed rate from 0.05 to 0.1mm/min but further increase in FR from 0.1 to

0.2mm/min is not causing much impact on the MRR. After machining the workpiece up to a certain depth the cutting energy of abrasives diminishes owing to accumulation of the debris at the interface and decreases the MRR after certain value.

MRR is decreasing in both the cases of change in AS from 1 to 5 μ m and from 5 μ m to 10 μ m. It is known that number of abrasive particles in a defined working area gets reduced when the size of abrasives increases. Hence, low MRR in initial stage but, further increase in size makes coarser abrasives particles which cause excessive hammering on workpiece, as a result MRR increases. It is observed from the Fig. 3 that MRR has also been affected due to slight interactions between the control variables. The main impact of control variables in terms of response curves for raw data has been plotted for examining the parametric effects on the response characteristics.

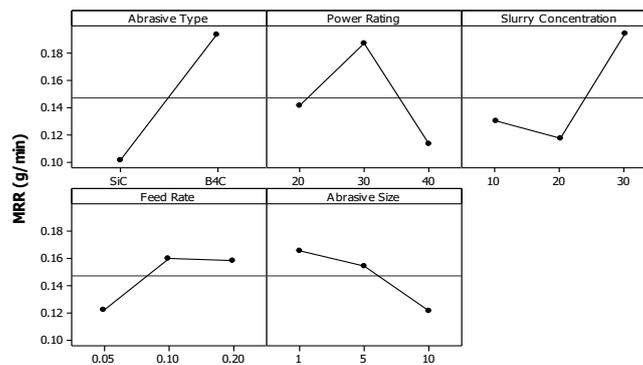


Fig. 3 Effects of USM parameters on MRR

A.1 Selection of optimal levels

ANOVA test was conducted on the experimental data, to estimate the contribution of each factor towards MRR for ultrasonic machining of Titanium. Tables 4 gives the un-pooled ANOVA for raw data and experimental analysis

Table 4 ANOVA for MRR (Means)

Source	DF	SS	MS	F	P	p (%)
AT	1	0.0380	0.0380	69.32	0.00	39.62
PR	2	0.0165	0.00825	15.08	0.005	17.21
SC	2	0.0203	0.01015	18.51	0.003	21.17
FR	2	0.0055	0.00275	05.04	0.052	5.74

shows that FR is a non-significant control variable for MRR. The response table for mean values (Table 5) reinforced the selection of optimal levels i.e. second level of AT (A₂), second level of PR (B₂) and third level of SC (C₃).

AS	2	0.0065	0.00325	05.95	0.038	6.78
AT*PR	2	0.0059	0.00295	05.45	0.055	6.15
Residual Error	6	0.0032	0.000533			3.33
Total	17	0.0959				

DF - degrees of freedom, p- Percentage Contribution, MS - Mean squares, SS - sum of squares, P- probability value , F-ratio of variance of a source to variance of error

Table 5 Response Table for MRR (Means)

Level	Abrasive Type	Power Rating	Slurry Concentration	Feed Rate	Abrasive Size
1	0.1013	0.1413	0.1302	0.1225	0.1660
2	0.1932	0.1871	0.1174	0.1604	0.1547
3	----	0.1135	0.1942	0.1589	0.1211
Delta	0.0919	0.0736	0.0768	0.0379	0.0449
Rank	1	3	2	4	5

A.2

Estimation of optimum response characteristics

Optimum value of MRR is forecasted at chosen levels of major control variables–AT(A₂), PR(B₂) and SC(C₃) (Table 5).

The mean MRR can be estimated as:

$$\mu_{MRR} = \bar{A}_2 + \bar{B}_2 + \bar{C}_3 - 2\bar{T} \tag{1}$$

Where,

$$\bar{T} = \text{mean MRR} = (\Sigma R_1 + \Sigma R_2 + \Sigma R_3) / 54 = 0.139965 \text{ mm}^3/\text{min}$$

Table 3 and Table 5 are used for the values of R₁, R₂, R₃ and \bar{A}_2, \bar{B}_2 & \bar{C}_3 respectively

$$\mu_{MRR} = 0.1932 + 0.1871 + 0.1942 - 2(0.139965) = 0.29457 \text{ mm}^3/\text{min}.$$

The 95 % confidence intervals of confirmation experiments (CI_{CE}) and population CI_{POP} are:

$$CI_{CE} = \pm 0.06125 \quad \text{and} \quad CI_{POP} = \pm 0.030624$$

Therefore, the predicted 95 % CI_{CE} is:

$$\mu_{MRR} - CI_{CE} < \mu_{MRR} < \mu_{MRR} + CI_{CE}$$

$$0.23332 < \mu_{MRR} < 0.35582$$

The 95% CI_{POP} is:

$$\mu_{MRR} - CI_{POP} < \mu_{MRR} < \mu_{MRR} + CI_{POP}$$

$$0.26395 < \mu_{MRR} < 0.3252$$

B. Influence of USM parameters on Surface Roughness

Mean values of SR for each control variable at various levels are represented in Fig. 4. It is found that SR is more when B₄C is used as abrasive. As B₄C is harder than SiC, therefore it leads to deeper penetration without fracture and hence expected to be more SR with use of B₄C abrasives. It is found that with increase in PR from 20mu to 30mu, SR increases and then decreases with further increase in PR from 30mu to 40mu. With the increase in PR, a substantial increase in the machining rate increases the crater size and hence deteriorates the surface finish. The SR increases when the SC increases from 10% to 20%, and there is slightly decrease in SR as the SC enhanced from 20% to 30%. This is due to the fact that increase in SC causes the loss of cutting energy which finally decreases the SR. There occurs no change in SR after increasing FR from 0.05 to 0.1, but it decreases with further increase in FR from 0.1 to 0.2. This happens because cutting energy of abrasives diminishes owing to accumulation of the debris at the interface and improves the surface quality. The SR decreases with increase in AS from 1µm to 5µm, but it increases with increase in AS from 5µm to 10µm. It is expected that number of abrasive particles gets reduce in a defined working area as size of abrasives increased. Hence, low SR in initial stage but, later coarser abrasives particles cause excessive hammering on workpiece, as a result SR increases. The main effects of control variable for raw data were plotted for investigating the parametric outcomes on the SR.

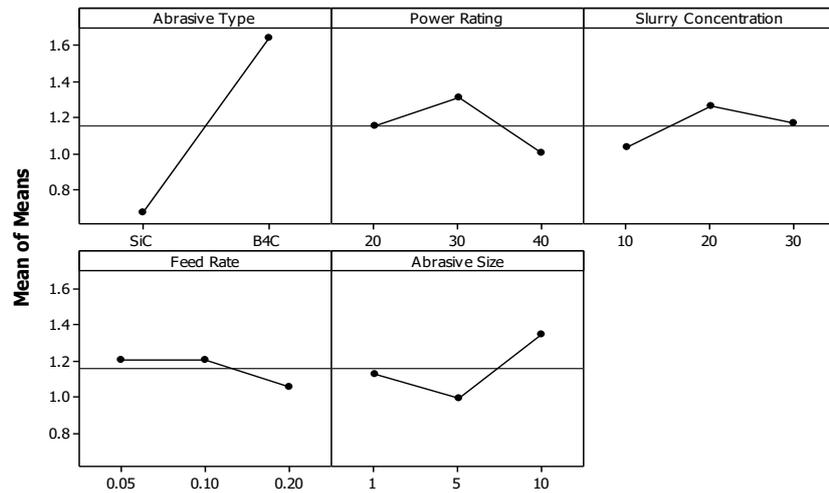


Fig. 4: Effects of USM parameters on SR (Means)

B.1 Selection of optimal levels

Table 6 presents the ANOVA results for SR. It is found that feed rate and slurry concentration are non-significant parameters for SR.

Table 6 ANOVA for SR (Means)

Source	DF	SS	MS	F	P	p (%)
AT	1	4.17990	4.17990	217.44	0.000	70.32
PR	2	0.28180	0.14090	7.33	0.024	4.74
SC	2	0.15846	0.07923	4.12	0.075	2.67
FR	2	0.09399	0.04700	2.44	0.167	1.58
AS	2	0.37367	0.18684	9.72	0.013	6.29
AT*PR	2	0.74078	0.37039	19.27	0.002	12.46
Residual Error	6	0.11534	0.01922			1.94
Total	17	5.94396				

Table 7 Response Table for SR

Level	AT	PR	SC	FR	AS
1	0.6756	1.1519	1.0358	1.2064	1.1265
2	1.6393	1.3134	1.2642	1.2106	0.9985
3	----	1.0071	1.1723	1.0553	1.3473
Delta	0.9638	0.3063	0.2284	0.1553	0.3488
Rank	1	3	4	5	2

The ANOVA results showed that abrasive type with a percent contribution of 70.32 %, AS with a percent contribution of 6.29 %, interaction of AS and PR with a percent contribution of 12.46 % and PR with a percent contribution of 4.74 % are the most effective factors.

As SR is the ‘smaller the better’ kind of attribute, main effects graphs for mean (Fig. 5) shows that the first level of abrasive type (A_1), third level of power rating (B_3) and second level of abrasive size (E_2) correspond to the minimum value of SR. The response table for mean (Tables 7) reinforced the selection of optimal levels.

B.2 Estimation of optimum response characteristics

Optimum value of SR is forecasted at the chosen levels of major control variables–AT (A_1), PR (B_3) and AS (E_2) (Table 7):

$$\mu_{SR} = (\bar{A}_1) + (\bar{B}_3) + (\bar{E}_2) - 2(\bar{T}) \tag{2}$$

Where, \bar{T} = Overall mean of SR = $(\Sigma R_1 + \Sigma R_2 + \Sigma R_3) / 54 = 1.15778$

(Table 3 and Table 8 are used for providing the values of R_1 , R_2 , R_3 and \bar{A}_1 , \bar{B}_3 & \bar{E}_2 respectively)

$$\mu_{SR} = 0.6756 + 1.0071 + 0.9985 - 2(1.15778)$$

$$\mu_{SR} = 0.36564$$

The 95 % confidence intervals of confirmation experiments (CI_{CE}) and population CI_{POP} are:

$$CI_{CE} = \pm 0.2772 \text{ and } CI_{POP} = \pm 0.1386$$

Therefore, the predicted 95 % CI_{CE} is: $\mu_{SR} - CI_{CE} < \mu_{SR} < \mu_{SR} + CI_{CE}$
 $0.08844 < \mu_{SR} < 0.64284$

The 95% CI_{POP} is: $\mu_{SR} - CI_{POP} < \mu_{SR} < \mu_{SR} + CI_{POP}$

$$0.22704 < \mu_{SR} < 0.50424$$

Optimal values of control variables at their chosen levels are as under:

- i. First level of AT (A_1): Silicon Carbide
- ii. Third of PR (B_3): 40 machine unit
- iii. Second level of AS (E_2): 5 μm
- iv.

IV. SURFACE CHARACTERIZATION

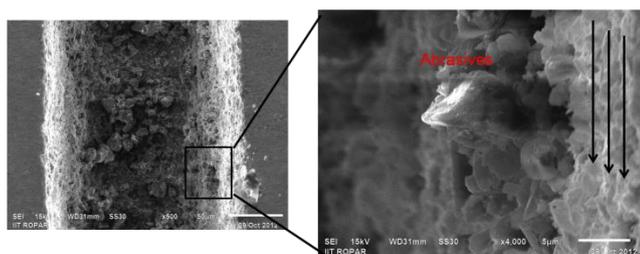
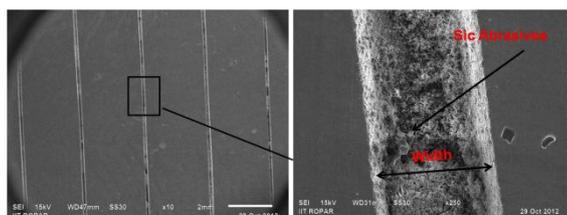


Fig. 8. (a) Open Microchannels on Ti Substrate (b) Zoomed view of Microchannel showing stuck abrasives in the cavity

Fig. 8. (b) A machined microchannel (b) Mechanical abrasion by the abrasive particles at side wall of the channel

V. CONCLUSION

In present work, μ -channels have been fabricated on pure-Ti using ultrasonic machining. The effect of different input parameters was also investigated on response characteristics. The following conclusions were found out by this research work:

1. The result shows that it is feasible to machine 3D open microchannels over a Ti plate using ultrasonic machining.
2. The MRR of pure-Ti during μ -USM was significantly affected by abrasive type (39.52%) followed by slurry concentration (21.11%) and power rating (17.20%). The optimal setting suggested by Taguchi method for MRR maximization is $A_2B_2C_3$ i.e. abrasive type: B_4C ; power rating: 30 and slurry concentration: 30%.
3. The SR is mainly affected by abrasive type (70.32%), abrasive size (16.29%) and power rating (4.74%). The suggested optimal setting of process parameter for SR minimization is $A_1B_3E_2$ i.e. abrasive type: SiC; power rating: 40 and abrasive size: 5 μm .
4. The side wall of the channels is expected to be machined by abrasion mechanism.
5. The tool wear during the machining is high owing to relatively ductile nature of the work material.
6. From the visual analysis of SEM images there is no evidence of any surface damage in the form of heat affected zone or surface cracking. This shows that

The microstructure of the machined surface of Titanium workpiece was obtained for each machined sample by using field emission scanning electron microscopy (FE-SEM) and scanning electron microscopy (SEM) at different magnification level. The magnification levels were different for different machined samples. Figure 8 (a) & (b) represents open microchannels of 250 μm hydraulic diameter in a 5 mm thick Titanium substrate machined with 10 μm abrasive grains. The slurry concentration was kept high during this experimentation. The stuck abrasives can be seen in the fig. 8 (b). Nevertheless, the sidewall of the channel is almost vertical on most of the height except close to the bottom where edges become rounded due to the inhomogeneous wear of the tool. Microstructures with much smoother sidewalls can be obtained using much finer grains and low slurry concentration, with a diameter comprised between 1 and 5 μm , and applying a low static load.

titanium has got fairly good machinability with ultrasonic micromachining.

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