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ORIGINAL ARTICLE

Investigations into the effect of process parameters on surface roughness and burr formation during micro end milling of TI-6AL-4V

K. Vipindas[1] · **B. Kuriachen**[2] · **Jose Mathew**[1]

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Abstract As micromachining is finding a lot of applications in various fields such as biomedical, avionics, optics, and electronics, it is necessary to produce parts with good surface finish and minimum burr. In this paper, experimental investigations on the effect of spindle speed, feed and depth of cut on various responses such as surface roughness and top burr formation during the micro milling of Ti-6Al-4V with two different carbide tools with a diameter of 0.5 and 1 mm have been carried out. Three levels of cutting parameters with full factorial design were used for the experimentation. The burrs formed on the up milling side of the micro slot were analyzed in this study. A scanning electron microscope (SEM) was used to analyze the burrs formed and was quantified in term of its kerf width. The analysis of variance (ANOVA) was used to find the level of significance of cutting parameters on surface roughness and top burr formation. In addition, statistical predictive models were also developed to predict the responses in terms of cutting parameters. Finally, a cutting strategy was postulated to minimize the top burr in the micro end milling of a slot and was verified for a slot of 0.75-mm width.

Keywords Micro milling · Surface roughness · Up milling · Down milling · ANOVA

✉ B. Kuriachen
basilkuriachen@gmail.com

K. Vipindas
vipindas.k@gmail.com

Jose Mathew
josmat@nitc.ac.in

[1] Mechanical Engineering Department, NIT, Calicut, Calicut, India

[2] Mechanical Engineering Department, NIT, Mizoram, Mizoram, India

1 Introduction

Nowadays, design and manufacture of micro parts is one of the big challenges in the manufacturing sector because of a large demand for the micro products. Micro parts have gained its presence in various fields such as in optics, electronics, medicine, biomedical devices, communications, and avionics. Among the various micromachining processes, micro milling is considered to be one of the preferred methods to manufacture micro components due to its ability and flexibility to produce complex 3D parts. One of the main requirements of any micro part or feature produced is its surface quality. The main factors which prevent the achievement of this objective are formation of burrs along the edges of the micro end milled parts and surface roughness of the machined surface. It was noticed that the top burrs formed on either side of the micro milled slots are different for full immersion micro end milling [1]. This difference is due to the fact that one side of the slot undergoes down milling while the other side undergoes up milling. The side wall where up milling takes place has smaller burrs than the side where down milling takes place. Presence of burrs and poor surface roughness of the machined parts raises lots of issues, such as it affects proper fitting and assembly of the parts and dimensional accuracy [2]. Also, the presence of burrs adds an additional process such as deburring, thereby increasing the production cost and time. Moreover, deburring of micro parts is very difficult compared to macro parts and, in many cases, the size of the burr will be comparable with the size of the micro features.

Basic mechanism of micromachining is different from the conventional macro machining because of edge radius effect and minimum chip thickness. Chip is formed when the uncut chip thickness is above the minimum uncut chip

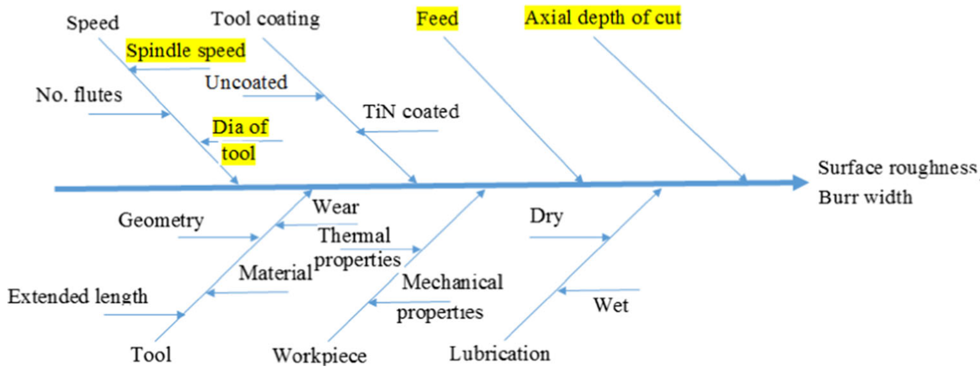


Fig. 1 Ishikawa diagram

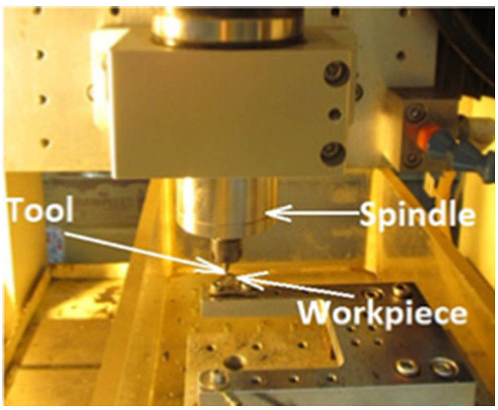


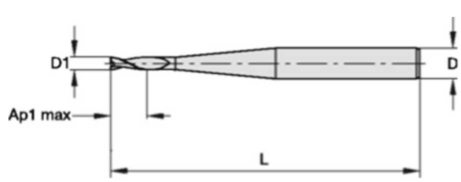
Fig. 2 Experimental setup

thickness. This change in chip formation is known as minimum chip thickness effect. Kim et al. [3] suggested that when feed per tooth is smaller than the cutting edge radius, a chip may not be formed at each tool passage. Yuan et al. [4] presented an analytical expression for the minimum cutting thickness. Son et al. [5] have reported that the type of workpiece material such as micro structure, hardness, and phase influence on minimum chip thickness. Different studies were carried out on analyzing the influence of size effect on cutting force and surface finish [6, 7]. Biermann and Kahnis [8] investigated the effect of down scaling on the tool deflection.

Surface roughness, which is one of the most important factors that influences the quality of a component, has been studied extensively. Many surface roughness models have been developed using different methods. Alauddin et al. [9] built a mathematical model which were first- and second-order polynomials using computer-aided analysis method. Ozel et al. [10] studied micromachining process performance using uncoated and cBN-coated micro-tools in terms of surface finish, burr formation, and tool wear. The effect of cutting parameters on surface roughness was reported in [11–13]. Wang et al. [11] used the response surface method to investigate the effect of cutting parameter and tool diameter on surface. Use of a lubricant on end milling and micro end milling process has been investigated to study its influence on reducing tool temperature [14], surface roughness [15], and burr [16]. The effect of different lubricant conditions such as dry machining, jet application, minimum quantity lubrication (MQL) on surface finish, and burr were also reported in literature [17, 18]. Shokrani et al. [19] studied the effect of cryogenic cooling using liquid nitrogen on surface integrity of Ti-6Al-4V alloy in end milling operation. the analysis of variance (ANOVA) and response surface methodology were used for analyzing the machining parameters on surface roughness, micro channel width dimension, micro channel shape, etc. in [20–26].

Researchers have suggested techniques for reducing burr by changing process parameters, such as lowering depth of cut, increasing cutting speed [27], and use of larger rake angles [28]. Chan et al. [29] described that the size of the top burr is affected by the ratio of the axial

Fig. 3 Tool specifications



Dimensions in mm					
D1	D	Ap1 max	L	No. of flutes	Helix Angle
0.5	3	1	38	2	30^0
1.0	3	2	38	2	30^0

Table 1 Process parameters and their levels

Factors	Level 1	Level 2	Level 3
Spindle speed (rpm)	1000	3000	5000
Feed (mm/min)	2	6	10
Depth of cut (mm)	0.05	0.1	0.15

depth of cut to the radius of the milling cutter. Influence of in-plane exit angle on the burr formation during micro milling has been studied and reported in literature [30–32]. Chern [32] proposed that the in-plane exit angle should be near to 150° for minimum burr. Saptaji et al. [33] investigated the effect of edge strengthening by changing the work surface geometry and by introducing a taper in the micro milling tool. The result suggests that a combination of the largest taper and large side edge angle produces minimum burr. Lekkala et al. [34] and Mathai et al. [35] investigated the effect of process parameters such as spindle speed, feed rate, tool diameter, depth of cut, and number of flutes on burr formation. Chu and Dornfeld [36] developed two approaches for tool path planning of 2D polygons. The first approach generates exit-free tool paths by offsetting the workpiece edges with an appropriate width of cut. The second one locally adjusts tool positions on given tool paths, to avoid tool exits occurring around the workpiece vertices.

The above mentioned papers discussed about the factor affecting the surface finish and burr formation during micro milling operation and most of the studies were concentrated on micromachining of easy-to-machine materials. There were very few papers which were concentrated on titanium alloys especially Ti-6Al-4V. It is being used in many fields like aerospace, biomedical, etc. because of its superior properties such as resistance to heavy loads, lightness, high specific ultimate tensile strength, bio-compatibility, low thermal and electrical conductivity, corrosion and stress-corrosion resistance. One of the main drawbacks of micro milling is the formation of burr while machining. So, it is necessary to know the factors which influence the formation of burr while producing micro slots/channels. Nowadays, industries are moving towards abandoning the use of lubricants in machining operations due to environmental concerns and cost of handling the lubricants. Because of this reason, even though there are numerous studies on the use of flood and bath lubrication in micro machining, this study mainly concentrated on the influence of cutting parameters on burr formation and surface finish during micro end milling under dry machining condition.

Table 2 Experimental results on surface roughness and top burr width on up milling side

Sl No.	A: spindle speed	B: Feed	C: Depth of cut	Surface roughness		Burr width on up milling side	
				0.5-mm tool	1-mm tool	0.5-mm tool	1-mm tool
	rpm	mm/min	mm	nm	nm	μm	μm
1	1000	2	0.05	112	115	84.3	87.4
2	1000	2	0.1	176	138	130	50.5
3	1000	2	0.15	190	179	148	65.2
4	1000	6	0.05	137	182	118	78.6
5	1000	6	0.1	193	195	89	58.6
6	1000	6	0.15	219	225	97.7	68.6
7	1000	10	0.05	158	198	77.4	64
8	1000	10	0.1	213	201	90.3	46.8
9	1000	10	0.15	252	223	54.7	59.6
10	3000	2	0.05	87	81	32.6	135
11	3000	2	0.1	147	109	89	114
12	3000	2	0.15	71	137	166	79.4
13	3000	6	0.05	97	88	40.1	123
14	3000	6	0.1	103	119	67	71.4
15	3000	6	0.15	113	163	98.3	99.3
16	3000	10	0.05	109	91	38.7	95.2
17	3000	10	0.1	173	147	46.1	87.4
18	3000	10	0.15	182	183	32.6	91.4
19	5000	2	0.05	146	89	76.1	111
20	5000	2	0.1	163	155	56.2	75.5
21	5000	2	0.15	190	161	92.6	91.4
22	5000	6	0.05	131	133	69.5	99.2
23	5000	6	0.1	137	173	128	71.4
24	5000	6	0.15	156	275	140	110
25	5000	10	0.05	123	234	79.1	75.5
26	5000	10	0.1	147	272	129	68.9
27	5000	10	0.15	159	324	92.6	78.2

In this paper, a study on surface roughness and burr formed, especially top burr, is performed for various cutting parameters such as spindle speed (s), feed (f), and depth of cut (d) for two different tool diameters during micro end milling of Ti-6Al-4V. Three levels of values were used for each of the cutting parameters. A statistical method of analysis of variance (ANOVA) was used to find the relation among spindle speed, feed, and depth of cut on surface roughness. Burrs formed on top of the slot were observed and its width was analyzed on the up milling and down milling side of the slot. Finally, a cutting strategy was suggested to minimize the top burr and was experimentally verified the same.

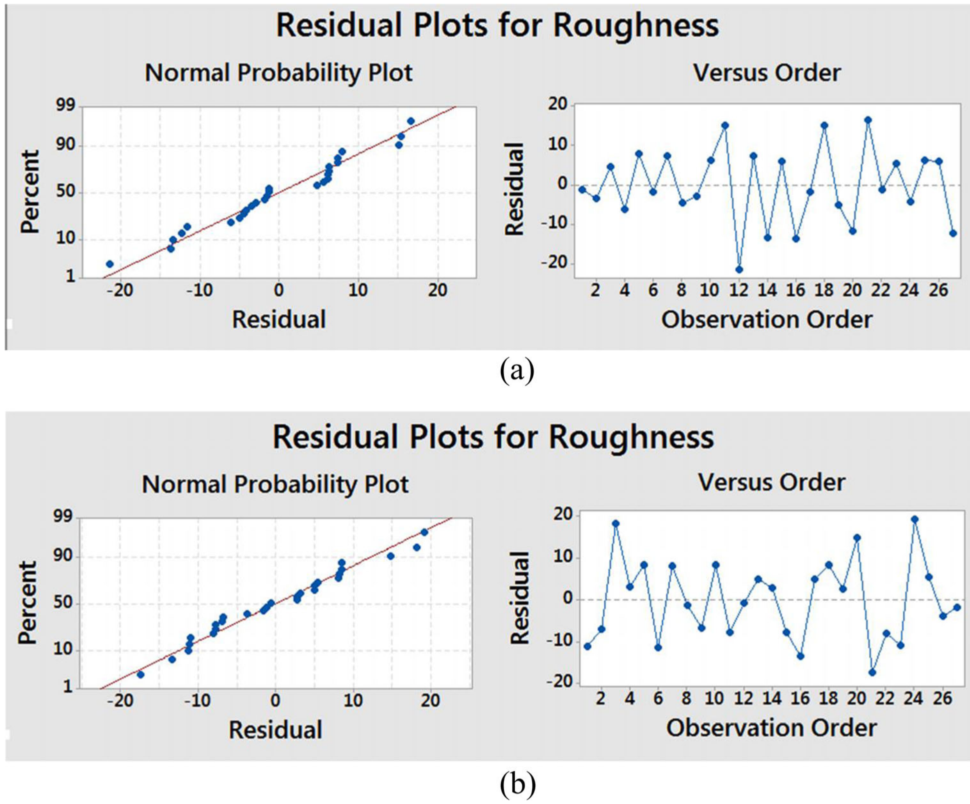


Fig. 4 Residual plot surface roughness **a** for tool diameter 0.5 mm and **b** for tool diameter 1.0 mm

2 Experimental setup

Experiments were performed on multipurpose Micro-machining center (DT110, Mikrotools, Singapore) with TiN-coated tools having an effective cutter diameter of 500 and 1000 μm. The effect of tool diameter, spindle speed, axial depth of cut, and feed was studied in terms of surface roughness and top burr formed on either side of the slot. Micro slot milling of a 2-mm-long straight channels were conducted. For every experimental run, average surface roughness (Ra) and total top burr width on the up milling and down milling side were measured.

Table 3 Modified ANOVA table for surface roughness with a 0.5-mm diameter tool

Source	Sum of squares	Df	Mean square	*F* value	*p* value prob > *F*
Model	0.037	6	6.18E-03	11.38	< 0.0001
A-spindle speed	4.93E-03	1	4.93E-03	9.09	0.0068
B-feed	3.04E-03	1	3.04E-03	5.61	0.0281
C-depth of cut	0.01	1	0.01	19.11	0.0003
AB	3.85E-03	1	3.85E-03	7.1	0.0149
AC	1.85E-03	1	1.85E-03	3.41	0.0797
A^2	0.013	1	0.013	23.96	< 0.0001
Residual	0.011	20	5.43E-04		
Cor total	0.048	26			

Table 4 Modified ANOVA table for surface roughness with a 1-mm diameter tool

Source	Sum of squares	Df	Mean square	*F* value	*p* value prob > *F*
Model	0.089	6	0.015	29.1	< 0.0001
A-spindle speed	1.42E-03	1	1.42E-03	2.8	0.1101
B-feed	0.028	1	0.028	54.9	< 0.0001
C-depth of cut	0.024	1	0.024	47.43	< 0.0001
AB	4.60E-03	1	4.60E-03	9.05	0.007
AC	2.47E-03	1	2.47E-03	4.85	0.0396
A^2	0.028	1	0.028	55.61	< 0.0001
Residual	0.01	20	5.09E-04		
Cor total	0.099	26			

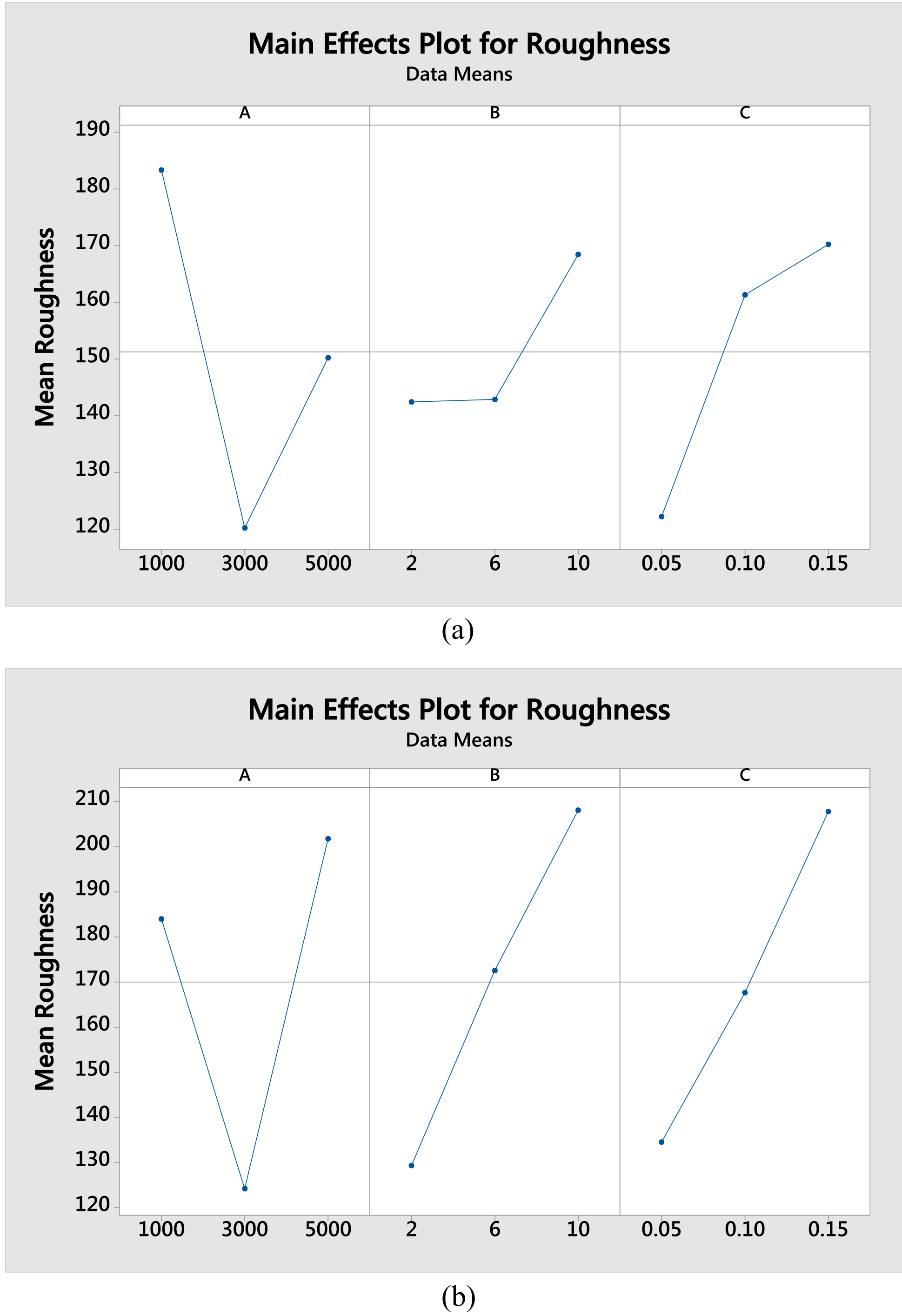
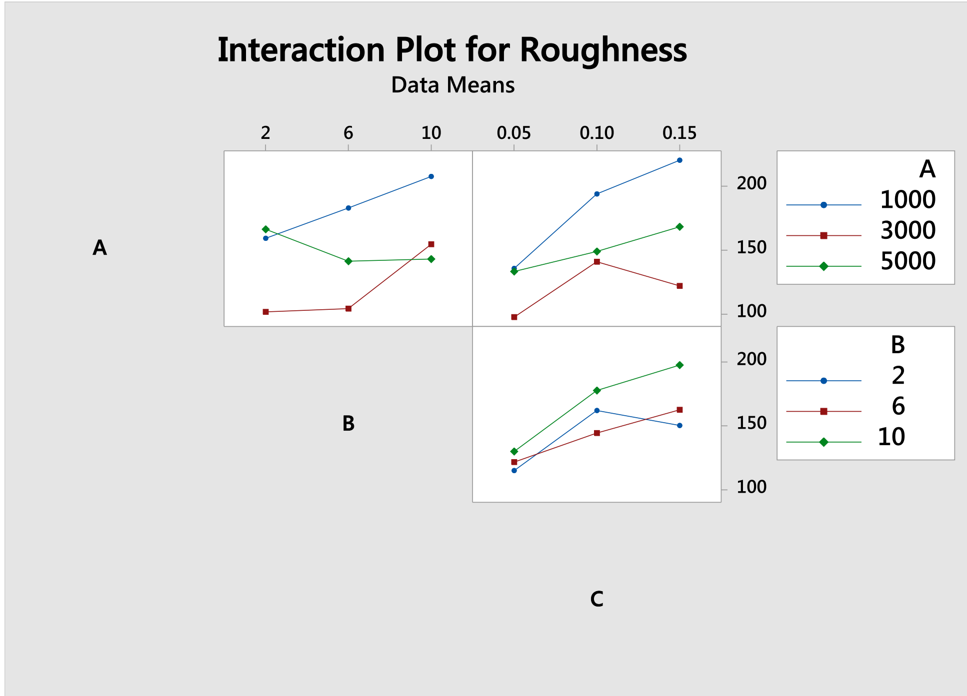


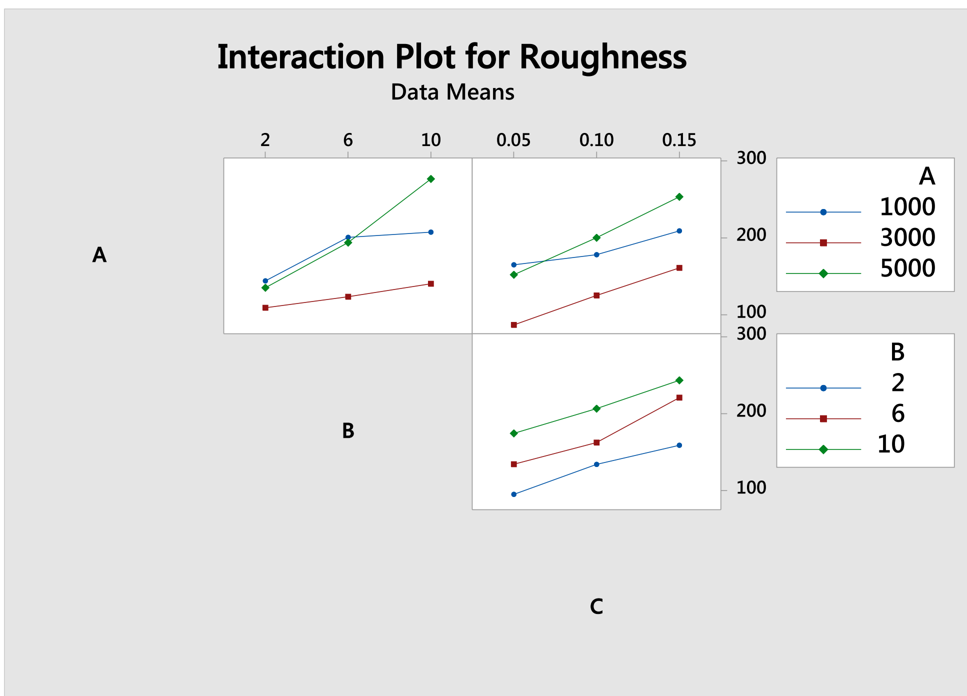
Fig. 5 Main effect plot for roughness (Ra) **a** for 0.5-mm tool diameter and **b** for 1.0-mm tool diameter

The workpiece material used in the experiment was Ti-6Al-4V. Figure 1 shows an Ishikawa diagram to find out various factors affecting surface roughness and burr width. Experimental set up is shown in Fig. 2. Figure 3 shows the tool specification used in the experiments.

Surface roughness was measured using Surftest SJ–410 (Mitutoyo) having a measuring range of (X axis) up to 50 mm, measuring range (detector) up to 800 μm and resolution 0.000125 μm with a 5-μm stylus tip diameter and a 0.25-mm cutoff length. A scanning electron microscope (HITACHI SU6600) was used for analyzing the burr.



(a)



(b)

Fig. 6 Interaction plot for surface roughness for **a** 0.5-mm-diameter tool and **b** 1 mm diameter tool

Experiments were conducted based on a three-level full factorial experimental design and the different levels of each parameter are listed in Table 1. Since the machining center used has maximum spindle speed limited to 5000 rpm, levels were chosen as such (cutting speed range used in the experiment is 1.57 to 15.7 m/min).

3 Results and discussion

ANOVA with level of confidence 95 % [37] was used to find out the significance of each parameter for both surface finish and burr width during micro end milling process. In the analysis, p value was used to determine the

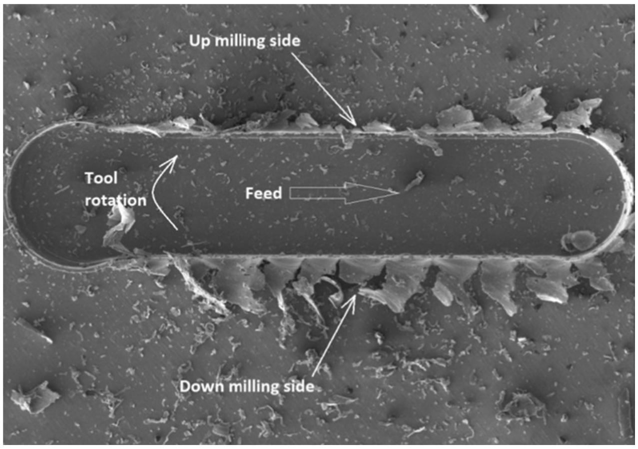


Fig. 7 Top burr formed during micro milling operation

significance of the factors or their interactions on response variables. Since the analysis was carried out at 95 % of confidence level, process parameters and their interactions will be significant if the p value is less than 0.05.

3.1 Analysis of surface roughness

In this study, surface roughness was used as a measure of quality of the slot surface produced by micro milling operation. Table 2 displays measured surface roughness (Ra) values for 0.5- and 1-mm-diameter micro milling tools, respectively.

Model adequacy was checked with the help of the residual plot of Surface roughness (Ra). Figure 4 shows the residual plots for Ra for both 0.5- and 1.0-mm tools. From the residual plots, it was understood that the residuals are normally distributed and there is no specific pattern.

From ANOVA Table 3, it could be observed that for a 0.5-mm tool diameter, the most significant factor on surface roughness is depth of cut followed by spindle speed and feed and by the factor interaction: spindle speed-feed interaction is most significant. Similarly, from ANOVA Table 4, it could be observed that for a 1-mm tool diameter, feed and depth of cut are most significant factors on surface roughness. Interactions affecting the response in the order of significance are: spindle speed-feed interaction followed by spindle speed–depth of cut interaction. Interaction plot for surface roughness for a 0.5- and 1-mm-diameter tool is shown in Figs. 5 and 6. A statistical model was developed for surface roughness for both tools as given below.

Statistical model for surface roughness for a 0.5-mm tool diameter in terms of coded factors:

$$\text{Roughness} = 0.12-(0.17\times A)+(0.013\times B)+(0.024\times C)-(0.018\times A\times B)-(0.012\times A\times C)+\left(0.047\times A^2\right) \quad (1)$$

Statistical model for surface roughness for a 1-mm tool diameter in terms of coded factors:

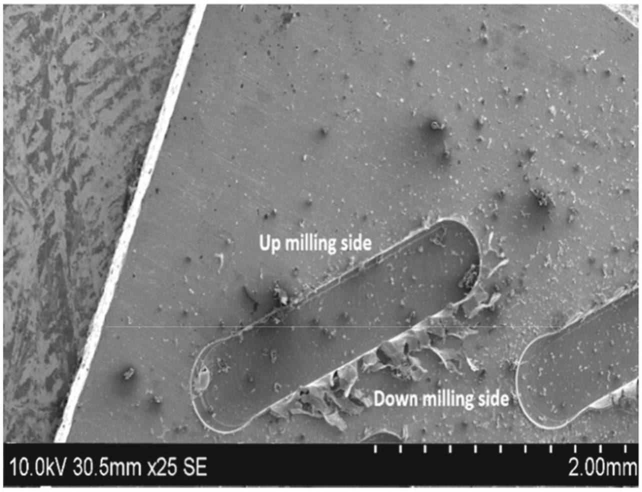
$$\text{Roughness} = 0.12+(8.889\,E{-}003\times A)+(0.013\times B)+(0.037\times C)+(0.020\times A\times B)+(0.014\times A\times C)+\left(0.069\times A^2\right) \quad (2)$$

The main effect implies direct influence of cutting parameters on surface roughness and interaction effect implies joint influence of two or more cutting parameters on surface roughness. Figure 5 shows the main effect plot for Ra for both tool diameter, i.e., 0.5 and 1.0 mm. From the main effect plot, it can be understood that surface roughness decreases as spindle speed increases, but after an optimal level, it increases. For both tools, increase in feed rate and depth of cut results in an increase in Ra value. Also, it can be noted that feed is more significant for large-diameter tools compared to small-diameter tools. Small-diameter tools produce better surface finish at higher feed and depth of cut. Hence, it can be concluded that better surface quality will be achieved by increasing spindle speed and up to middle level and decreasing feed and depth of cut.

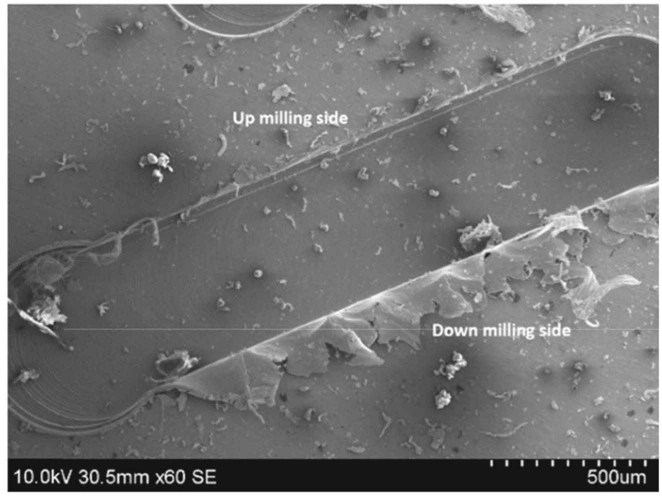
3.2 Analysis of top burr formation

Apart from surface roughness, burr formation is another parameter which is used as a measure of the quality of micro slots. In this study, it has been limited to the burrs formed on the top surface of the slot, which is commonly referred to as top burrs, during micro milling operation. SEM images were used to analyze the top burrs. Figure 7 shows an example of top burrs formed during micro milling operation and it is evident that quality of the micro machined slot is severely affected by the presence of this burr. As in the case of macro machining, burrs in micromachining cannot be neglected because size of the burr may be comparable with that of size of the machined feature.

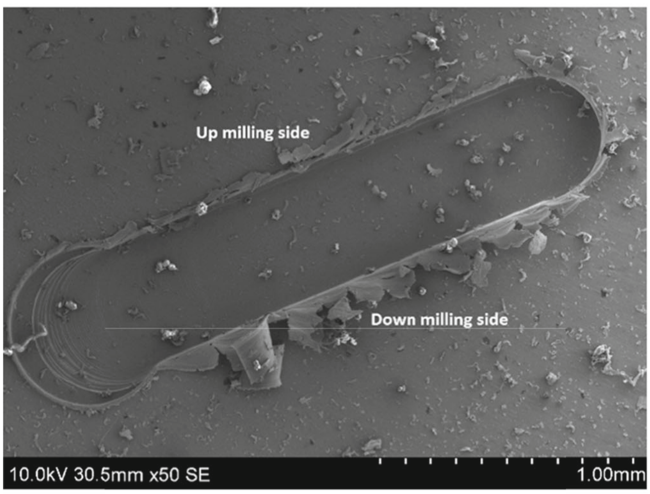
Figures 8 and 9 show some of the experimental results of top burr formation at various cutting parameters for tool diameter 0.5 mm and 1.0 mm respectively. In this experiment, a tool with a diameter equal to the width of the slot was chosen. It is evident from these figures that the cutting parameter influences the



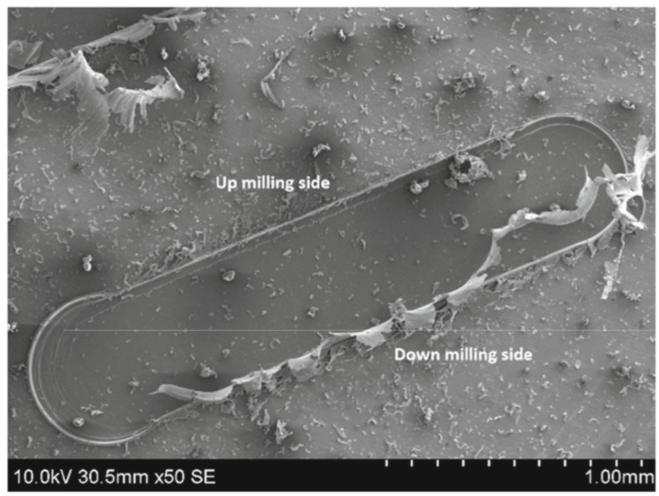
(a) s = 1000 rpm, d = 0.05 mm



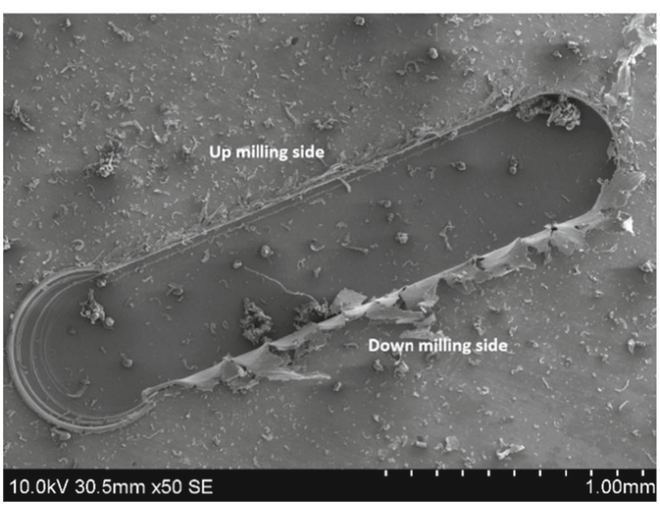
(b) s = 1000 rpm, d = 0.10 mm



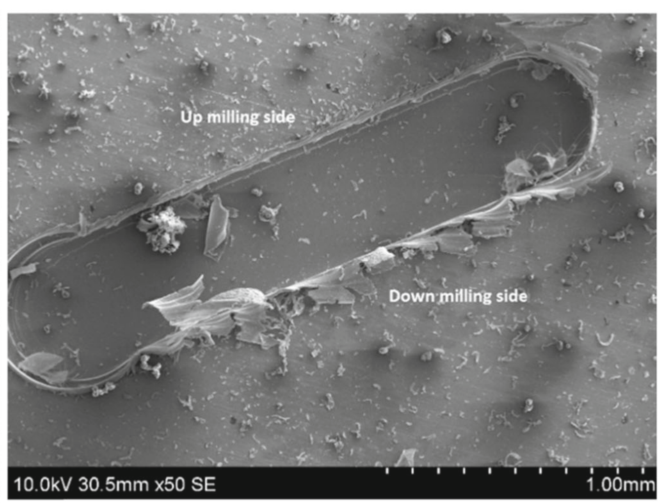
(c) s = 1000 rpm, d = 0.15 mm



(d) s = 3000 rpm, d = 0.05 mm

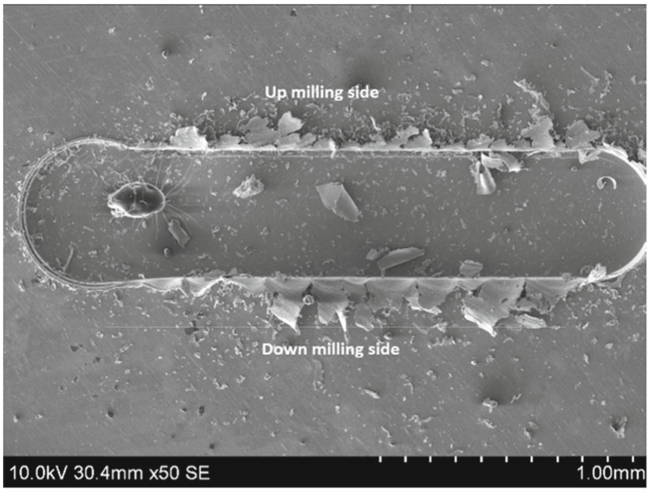


(e) s = 3000rpm, d = 0.10 mm

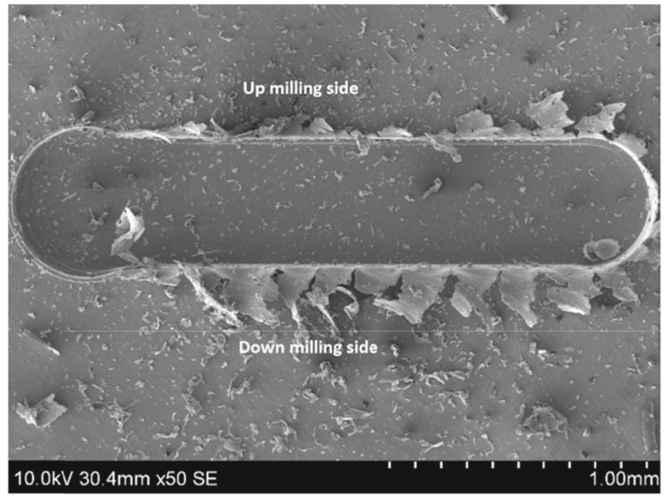


(f) s = 3000 rpm, d = 0.15 mm

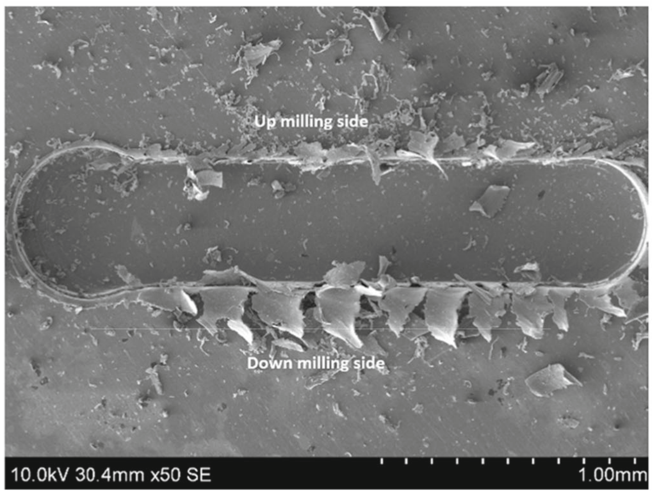
Fig. 8 Burrs formed on the top surface of the micro slot for each cutting parameter for a feed of 10 mm/min with a 0.5-mm diameter tool



(g) s = 5000 rpm, d = 0.05 mm



(h) s = 5000 rpm, d = 0.10 mm

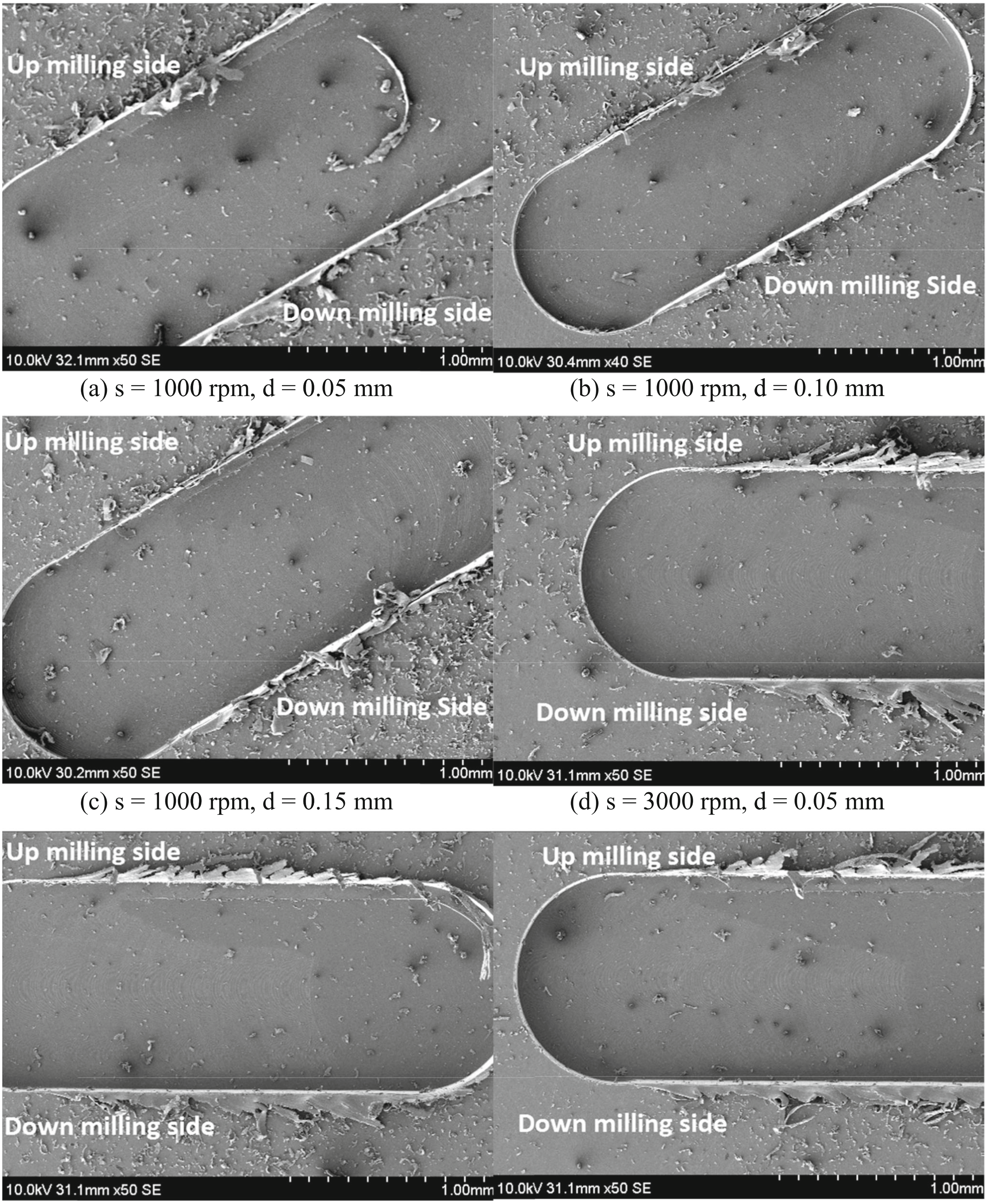


(i) s = 5000 rpm, d = 0.15 mm

Fig. 8 (continued)

formation of top burrs. It is also evident from these figures that top burrs formed on either side of the slot are different. This is due to the fact that when the tool diameter is equal to the slot width, one side of the slot undergoes up milling and other side of the slot is subjected to down milling. This is based on the cutting velocity direction on each side of the slot as shown in Fig. 10. Hence, the slot side where the cutting direction is parallel to the tool feed direction will be the up milling side and the slot side where cutting direction is opposite to the tool feed direction will be the down milling side. It can be noted that more burrs are formed on the down milling side of the slot compared to the up milling side of the slot. Since burr formation is less on up milling side, more emphasis has been given to analyze and characterize burrs formed on up milling side rather than the down milling side. Therefore, from here onwards, burr width (BW) implies top burr width on up milling side.

Figure 11 shows the residual plots for burr width with a 0.5-mm-diameter tool. It was observed that the residuals are normally distributed and there is no specific pattern in residual vs run order. From the ANOVA (Table 5), it could be noticed that for a 0.5-mm tool diameter, the most significant factor on top burr formation is depth of cut followed by feed. Interactions affecting the top burr formation are: most significant is feed-depth of cut interaction followed by spindle

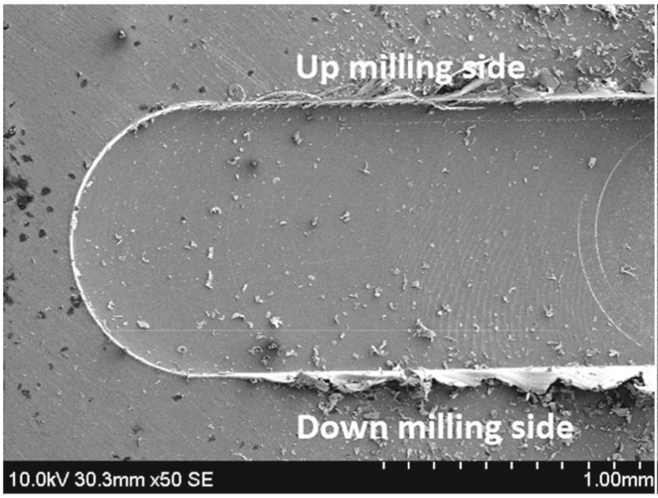


(a) s = 1000 rpm, d = 0.05 mm (b) s = 1000 rpm, d = 0.10 mm

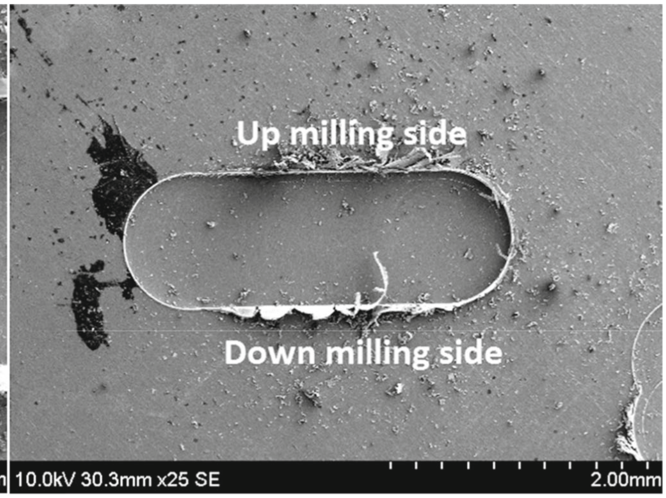
(c) s = 1000 rpm, d = 0.15 mm (d) s = 3000 rpm, d = 0.05 mm

(e) s = 3000 rpm, d = 0.10 mm (f) s = 3000 rpm, d = 0.15 mm

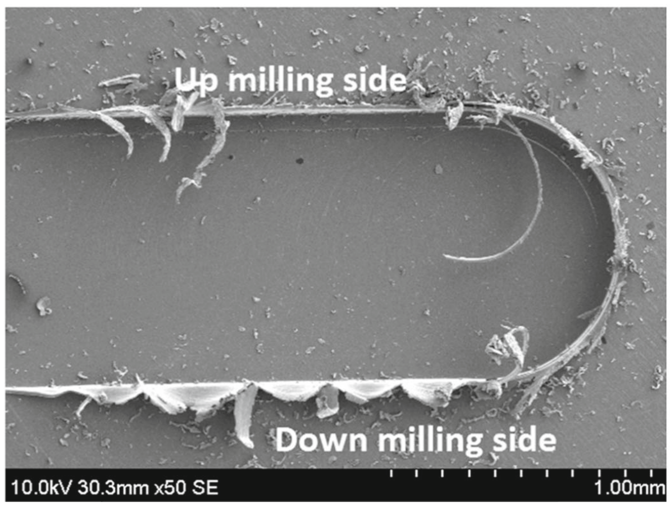
Fig. 9 Burrs formed on top surface of the micro slot for each cutting parameter for a feed of 10 mm/min with a 1-mm diameter tool



(g) s =5000rpm, d = 0.05 mm



(h) s = 5000 rpm, d = 0.10 mm



(i) s = 5000rpm, d = 0.15 mm

Fig. 9 (continued)

speed-feed interaction. Figure 12 shows main effect plot for top burr width with a 0.5-mm-diameter tool and it can be understood that as the spindle speed increases to 3000 rpm, burr width reduces, but a further increase in the spindle speed resulted in increase in burr width. Also, it can be noted that as feed increases, top burr width decreases, and with increase in depth of cut, top burr width increases. Figure 13 shows the interaction plot for top burr width for a 0.5-mm-diameter tool. In addition, a statistical model was developed to predict top burr width on the up milling side for a 0.5-mm diameter tool as given below.

Statistical model for top burr width for a 0.5-mm tool diameter in terms of coded factors:

$$\text{Burr width up milling} = 67.82-(1.46 \times A)-(13.02 \times B) + (17.04 \times C) + (17.97 \times A \times B) - (19.07 \times B \times C) + \left(29.54 \times A^2\right) \quad (3)$$

From the residual plot (Fig. 14) for a 1-mm-diameter tool, it can be noted that the residuals are normally distributed and there is no specific pattern in residual vs run order. From the ANOVA (Table 6), it can be observed that for a 1-mm tool diameter, the most significant factor on top burr formation is spindle speed followed by feed and depth of cut as well as feed-depth of cut interaction also

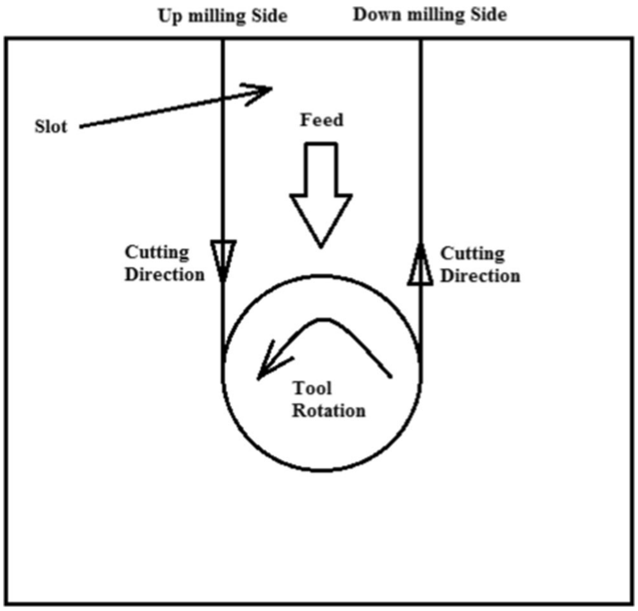


Fig. 10 Up milling and down milling side of a slot

found to be significant at 95 % confidence level. From the main effect plot (Fig. 15), it is understood that as spindle speed increases to 3000 rpm, top burr width initially increase but further increase in spindle speed results in a decrease in top burr width. In the case of feed, top burr width is found to be decreasing as feed increases. For an initial increase in depth of cut, top burr width was found to be decreasing, whereas further increase in depth of cut resulted in an increase in top burr width. Interaction plot for top burr width for a 1-mm-diameter tool is shown in Fig. 16. A statistical model was developed to predict top burr width on the up milling side for a 1-mm-diameter tool as given below.

A statistical model for top burr width for a 1-mm tool diameter in terms of coded factors:

$$Log_{10}(\text{Burr width up milling}) = 1.92 + (0.065 \times A) - (0.038 \times B) - (0.032 \times C) + (0.034 \times B \times C) - \left(0.12 \times A^2\right) + \left(0.10 \times C^2\right) \quad (4)$$

Fig. 11 Residual plot for top burr in up milling for a tool diameter 0.5 mm

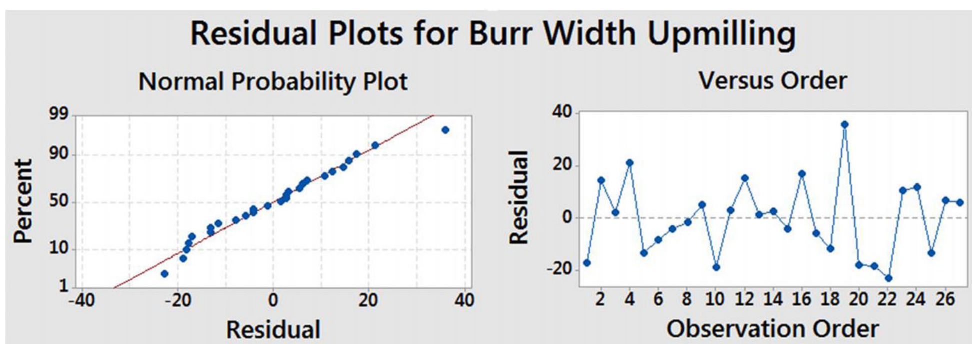


Table 5 Modified ANOVA table for top burr width with a 0.5-mm-diameter tool

Source	Sum of squares	df	Mean square	*F* value	*p* value prob > *F*
Model	21,792.81	6	3632.14	5.74	0.0013
A-spindle speed	38.43	1	38.43	0.061	0.8078
B-feed	3049.81	1	3049.81	4.82	0.0401
C-depth of cut	5225.83	1	5225.83	8.26	0.0094
AB	3877.21	1	3877.21	6.13	0.0224
BC	4366.27	1	4366.27	6.9	0.0161
A^2	5235.28	1	5235.28	8.28	0.0093
Residual	12,652.7	20	632.64		
Cor total	34,445.51	26			

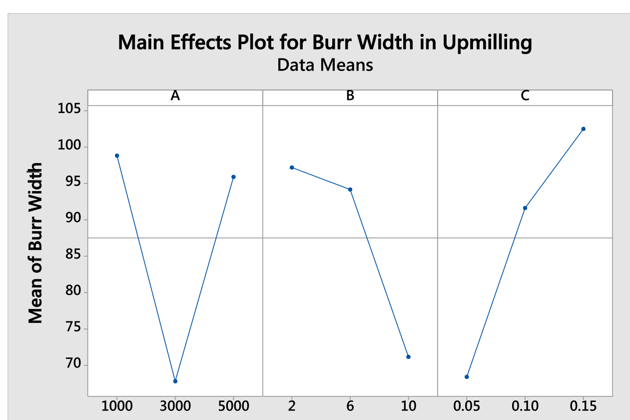


Fig. 12 Main effect plot for top burr width with a 0.5-mm-diameter tool

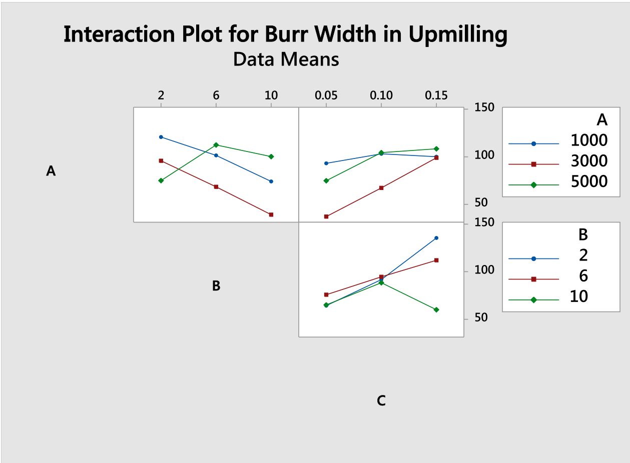


Fig. 13 Interaction plot for top burr width with a 0.5-mm-diameter tool

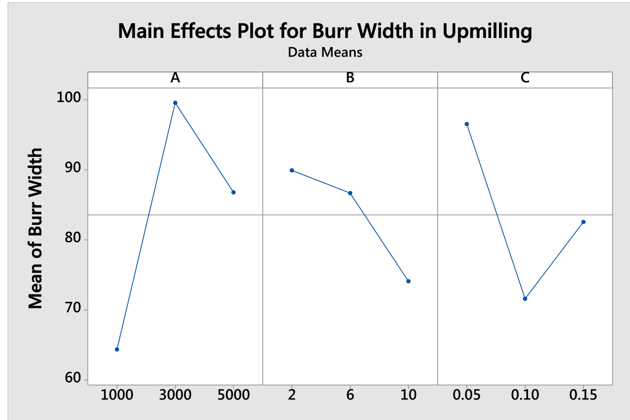


Fig. 15 Main effect plot for top burr width with a 1-mm-diameter tool

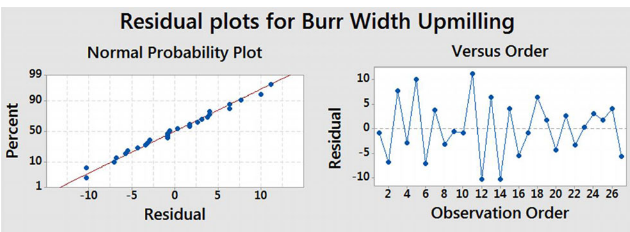


Fig. 14 Residual plot for top burr width with a 1-mm-diameter tool

In this study, it was found that during micro milling of slots on Ti-6Al-4 V, top burrs formed on the up milling side of the slot is less compared to the down milling side of the slot. In any machining process, one of the main objectives is to reduce burr; this finding can be used to create micro slots/channels with minimum top burrs. We can plan a tool path in such a way that slot walls are produced by up milling. Figure 17a shows a micro channel of width 0.5 mm produced by a tool of 0.5-mm diameter and (b) shows a micro channel of width 0.75 mm produced by a tool of 0.5-mm diameter. A schematic diagram of a tool path for this cutting is shown in Fig. 18. In the second case, the tool path was planned in such a way that both sides of the channels are produced by up milling. It is very clear from the figure that the slot produced by second method has a lesser top burr.

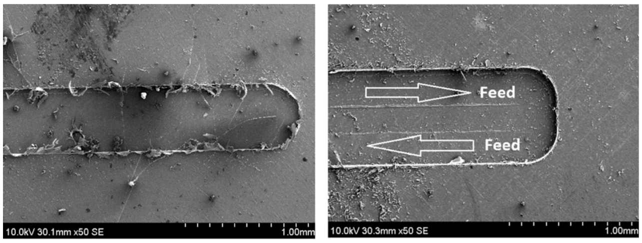
Table 6 Modified ANOVA table for top burr width with a 1-mm diameter tool

Source	Sum of squares	df	Mean square	*F* value	*p*-value Prob > *F*
Model	0.29	6	0.048	17.53	< 0.0001
A-spindle speed	0.077	1	0.077	27.99	< 0.0001
B-feed	0.026	1	0.026	9.6	0.0057
C-depth of cut	0.019	1	0.019	6.89	0.0163
BC	0.014	1	0.014	5.08	0.0355
A^2	0.091	1	0.091	33.37	< 0.0001
C^2	0.061	1	0.061	22.24	0.0001
Residual	0.055	20	2.74E-03		
Cor total	0.34	26			

3.3 Results of multi-objective optimization

In this study, a multi-objective optimization was performed using desirability function approach to find out the optimal process parameters to achieve the desired level of response. the desired level of response in this case is minimum surface roughness and minimum burr

Fig. 16 Interaction plot for top burr width with a 1-mm-diameter tool



(a) (b)

Fig. 17 **a** 0.5 mm micro channel produced by a 0.5-mm-diameter milling tool with the tool rotating in clock wise direction. **b** A 0.75-mm micro channel produced by a 0.5-mm-diameter tool with up milling cutting with tool rotating in a clockwise direction

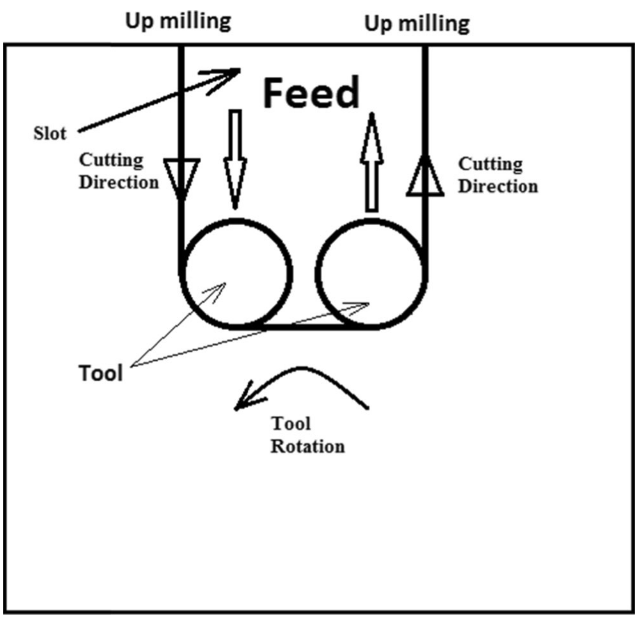


Fig. 18 Tool path for producing micro channel with up milling

formation. For a 0.5-mm-diameter tool, spindle speed 3147 rpm, feed 2 mm/min, depth of cut 0.05 mm were found to be the optimum set for minimizing both surface roughness and top burr width. For a 1-mm-diameter tool, spindle speed 1462 rpm, feed 2 mm/min, depth of cut 0.1 mm were found to be the optimum process parameters. Experiments were conducted at these settings to validate the model and the results are shown in Table 7. It can be noticed that deviation of experimental results for surface roughness are within 8.88 and 11.93 % for a 0.5- and 1-mm-diameter tool, respectively. Similarly for top burr width, the deviation of experimental results is within 6.89 and 9.88 % for a 0.5-mm and 1-mm-diameter tool, respectively.

4 Conclusion

Present study mainly concentrated on a fundamental understanding about micro end milling of Ti-6Al-4V during the fabrication of micro slot/channel. The effect of important cutting parameters such as spindle speed, feed, and depth of cut on surface roughness and top burr width with two different cutting tools having a diameter of 0.5 mm and 1 mm. A three-level full factorial experiment and ANOVA were adopted to conduct the experiments and to investigate the level of significance of each cutting parameter on response variables. In addition, a cutting strategy was postulated to minimize the top burr during the manufacturing of micro channels. Based on the experimental investigations, the following observations were drawn:

1. For a 0.5-mm-diameter tool, depth of cut and spindle speed are the most influencing factors on surface roughness followed by feed. In addition, the interaction of spindle speed-feed and spindle speed-depth of cut also significantly influence surface roughness.
2. Feed, depth of cut, interaction of spindle speed-feed and interaction of speed-depth of cut were the major factors on surface roughness for a 1-mm-diameter tool.
3. Increase in feed and depth of cut results in increase in surface roughness. Feed is found to be more significant on surface roughness for a 1-mm diameter tool than a 0.5-mm diameter tool.

Table 7 Comparison between calculated and experimental results for surface roughness and top burr width at optimum cutting parameter for 0.5 mm and 1 mm diameter tool

	Surface roughness (Ra)			Top burr width		
	Optimum value (nm)	Experimental result (nm)	% error	Optimum value (μm)	Experimental result (μm)	% error
0.5-mm-diameter tool	84.5	77	8.88	43.5	40.5	6.89
1-mm-diameter tool	134.9	151	11.93	68.8	62	9.88

4. At higher level of feed and depth of cut, a 0.5-mm-diameter tool produces better surface finish compared to a 1-mm-diameter tool.
5. For a 0.5-mm-diameter tool, it was found that feed and depth of cut are significant factors on top burr width, and there is an interaction between spindle speed-feed and feed-depth of cut which are also found to be significant. For a 1-mm-diameter tool, spindle speed, feed and depth of cut are significant factors on top burr width; also, there is an interaction of feed-depth of cut on top burr width.
6. For both tool diameters, higher feed resulted in decreases in top burr width.
7. Up milling side of the micro slot/micro channel produces lesser burr compared to down milling side. Based on this, a tool path was designed to create a micro channel in such a way that micro channel sides are created by up milling. For example, if we want to create a micro slot of 0.75-mm width, instead of using a 0.75-mm-diameter end mill tool, a 0.5-mm tool with a defined tool path can make a slot in such a way that slot walls are created by up milling (Fig. 18). Thereby, we can get a slot with reduced top burr. Confirmation experiment has shown that this strategy can produce better channel with reduced top burr.
8. Optimum cutting parameter for minimum surface roughness and minimum top burr width was found to be spindle speed 3147 rpm, feed 2 mm/min, depth of cut 0.05 mm for a 0.5-mm-diameter tool and spindle speed 1462 rpm, feed 2 mm/min, depth of cut 0.1 mm for a 1-mm-diameter tool.

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