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The effect of spindle speed, feed-rate and machining time to the surface roughness and burr formation of Aluminum Alloy 1100 in micro-milling operation

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ABSTRACT

This paper describes the characteristics and the cutting parameters performance of spindle speeds (n, rpm) and feed-rates (f, mm/s) during three interval ranges of machining times (t, minutes) with respect to the surface roughness and burr formation, by using a miniaturized micro-milling machine. Flat end-mill tools that have two-flutes, made of solid carbide with Mega-T coated, with 0.2 mm in diameter were used to cut Aluminum Alloy AA1100. The causal relationship among spindle speeds, feed-rates, and machining times toward the surface roughness was analyzed using a statistical method ANOVA. It is found that the feed-rate (f) and machining time (t) contribute significantly to the surface roughness. Lower feed-rate would produce better surface roughness. However, when machining time is transformed into total cut length, it is known that a higher feed-rate, that consequently giving more productive machining since produce more cut length, would not degrade surface quality and tool life significantly. Burr occurrence on machined work pieces was analyzed using SEM. The average sizes of top burr for each cutting parameter selection were analyzed to find the relation between the cutting parameters and burr formation. In this research, bottom burr was found. It is formed in a longer machining time compare the formation of top burr, entrance burr and exit burr. Burr formation is significantly affected by the tool condition, which is degrading during the machining process. This knowledge of appropriate cutting parameter selection and actual tool condition would be an important consideration when planning a micro-milling process to produce a product with minimum burr.

1. Introduction

Micro-manufacturing is defined as a scaling-down of conventional technologies or process in order to manufacture micro-products/features [1]. Micro-milling is one of micro manufacturing processes that have the ability to produce micro products with complex shape. Surface and size effect begins to dominate material respond and behavior due to the scaling-down effect [2]. Most of micro products such as medical equipment, micro-mold, micro tubular component, and so on need a high quality of finished surface. Product with high quality surface can be obtained by selecting appropriate cutting parameter, especially for surface finish cutting operation.

In micro-milling, material removing process is dominated by ploughing, rubbing, plastic and elastic deformation effects instead of cutting process [3]. The ploughing/rubbing process increases surface roughness and form burrs [1]. Therefore, surface roughness and burr formation can be used as an assessment to select the best cutting parameters.

Many researchers published their study on finding the relationship between cutting parameters and surface roughness. Wang et al. [4] explained that surface roughness increased linearly as the tool diameter and spindle speed increases; feed-rate is the most influential parameter when other parameters are constant. The research found that increasing the structure and tool stiffness, and decreasing the spindle chatter or vibration will improve work piece surface quality. Volger et al. [5] examined surface generation process in the micro-end milling of both single-phase and multiphase work piece materials. The paper explained that surface roughness R_a value at the bottom of slots produced in single-phase ferrite and

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pearlite does not monotonically increase as feed-rate increases, as in conventional machining operation. This effect is caused by minimum chip thickness concept. Vàzquez et al. [6] investigated the effect of varying cutting parameters such as spindle speed, depth of cut per pass, depth, feed per tooth and coolant applicant to surface roughness on aluminum and copper. The research exposed that surface roughness is mainly influenced by feed per tooth and coolant application. Rondriguez et al. [7] investigated the effect of cutting speed and machining time to surface roughness. However, there is no detail illustration in respect of tool condition during interval of time, surface roughness and burr formation.

On the other hand, Jin et al. [8] studied the influence of cutting parameters on the surface topography and cutting force in the micro-milling of AISI D2 Steel. The research found that the burr size and surface roughness increases at a low ratio of feed per tooth to cutting edge radius. Biermann and Kahnis [9] investigated the effect of a down-scaling on the tools deflection. The paper presented an adequate cutting parameter, cutting speed and feed per tooth to reduce tool deflection for specific tool diameter. The paper also revealed that an enlargement of cutting edge radius leads not only to a higher cutting force and to a lower surface quality, but also to a less tool wear. Meanwhile, Saptaji et al. [10] 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 largest taper and largest side edge angle produces minimum burrs.

Aurich et al. [11] defined burr as an undesirable or unwanted projection of the material formed as the result of the plastic flow from cutting and shearing operation. Deburing is a costly, time consuming and non-value-added operation. Consequently, it is very

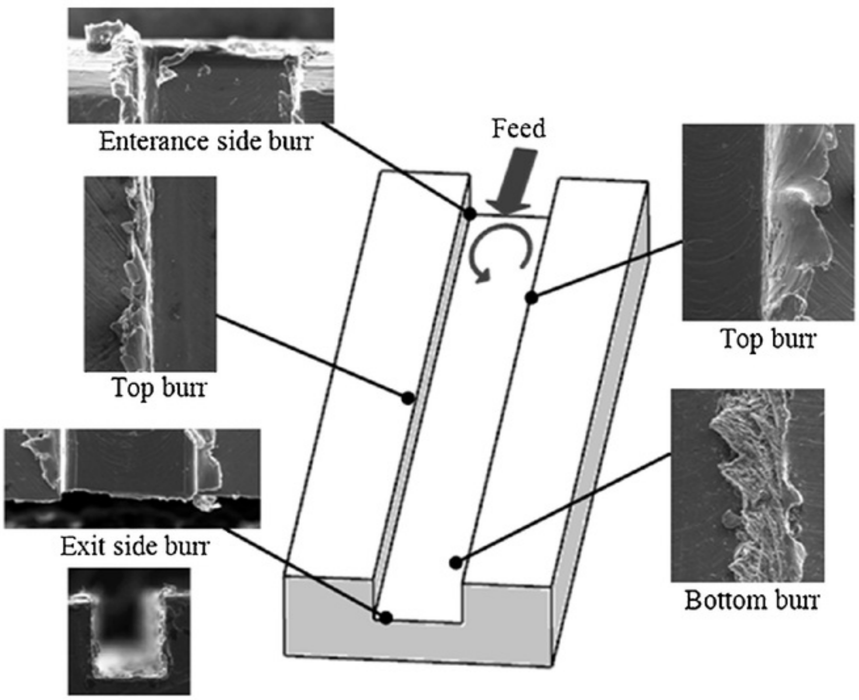


Fig. 1. Types of milling burrs.

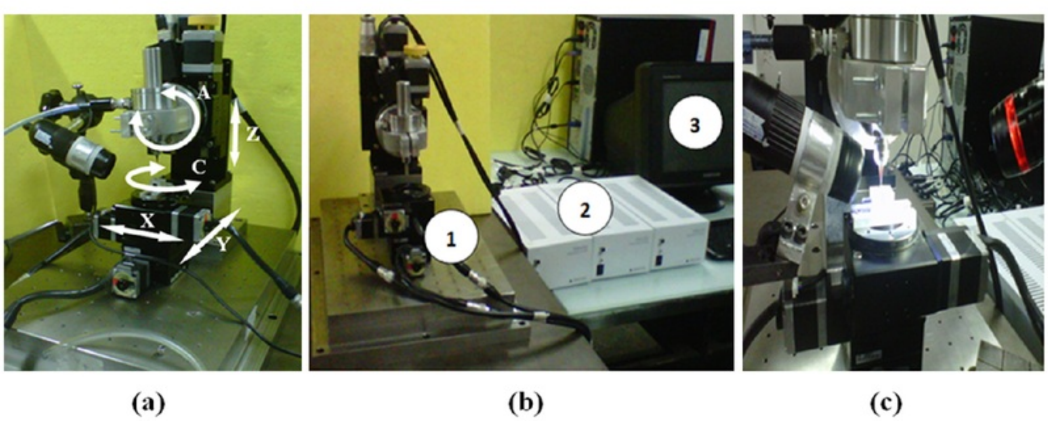
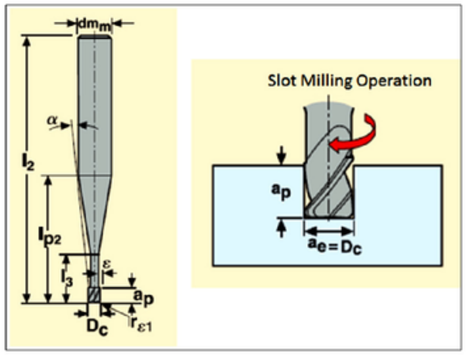


Fig. 2. (a) Miniaturized micro-scale 5-axis micro-milling (b) micro-milling machine and controller (c) during the cutting process.



Dimensions in mm										Max. cut depth rel. to αη (lαη)*					
D_c	dm_m	l_2	l_3	l_{p2}	a_p	ε	$r_{\varepsilon 1}$	α	z_n	0°	0,5°	1°	1,5°	2°	3°
0.2	3	40	–	5.7	0.3	–	–	14°	2	0.3	0.5	0.5	0.5	0.5	0.6

Fig. 3. Tool specifications [21].

important to understand and to control the burr occurrence in the cutting process. Chern [12] explained that the type of burr formed is dependent on the in-plane exit angle, ψ, and classified into five types which are (1) the knife-type burr; (2) the wave-type burr; (3) the curl-type burr; (4) the edge breakout burr; and (5) secondary burr. On the other hand, Hashimura et al. [13] classified burrs in face milling operation according to its location, burr shapes and burr formation mechanism. There are entrance burr, exit burr, side burr and top burr. Although Litwinski et al. [14] included bottom burrs in developing a tool path planning concept for micro end milling of pocket to minimize different characteristics such as surface roughness, top burr formation, and bottom burrs, there is no explanation about bottom burrs itself. Based on the experimental results performed in this research, it is found that there are bottom burrs formed in the bottom side of the micro-channel, as depicted in Fig. 1.

Lee and Dornfeld [15] explained that burr height is linearly proportional to feed and related to tool wear. For feed divided by the radius of a cutting edge <1, tool life increases as the cutting speed increases. Tool life was stated in number of holes, which is not applicable to other milling operation such as facing, slot and planar milling. Meanwhile, Chen et al. [16] described that the size of top burr is affected by the ratio of axial depth of cut to the radius of the milling cutter. Proper cutting speeds and a sharper tool reduce slot base burrs. Chu and Dornfeld [17] explained that the ratio of uncut chip thickness to the cutting edge radius is an important factor that influence the burr height. Biermann and Steiner [18] studied the influence of milling strategy, cutting speed, feed per tooth, lubrication method and the tool type in the size of top burr. Furthermore, Tang et al. [19] investigated the influence of radial depth of cut, cutting speed, feed speed and mesh size on the burr formation. A comprehensive study has perfomed by Lekkala et al. [20] to investigate the effect of spindle speed, feed-rate, tool diameter, depth of cut and number of flutes to burr formation. These papers revealed the effect of cutting parameters to burr formation. However, none of the papers explained the influence of machining time and tool condition to burr growth in micro-milling operation.

The above mentioned papers explained the characteristics of surface quality for various cutting parameters in micro-milling operation. Surface quality is indicated by surface roughness (R_a) and presence of burr. However, there is inadequate reference that stressing the importance of knowing appropriate cutting parameters and respected machining time with respect to surface quality. Only a few studies concluded the machining time in detail. In real micro part machining, knowing the effect of speed and feed only to the surface quality is not enough. An actual mapping between machining time and resulting surface quality using different cutting parameters must be clearly identified in advance since it is used to guide selecting suitable cutting parameters (e.g. feed rate). By knowing the feed rate, then machining time is converted easily into total cut length (the total length of cutting motion, mm). Eventually, the relationship between cut length and surface roughness can be derived. Since in designing tool path for micro part machining the total cut length is known, then based on that calculated cut length, one can select which cutting parameters would produce required surface quality.

Therefore, this paper presents a comprehensive study on surface roughness and burr formation for three interval ranges of machining time with three level variations of spindle speed and feed-rate in slot micro-milling operation. ANOVA statistical analysis was used

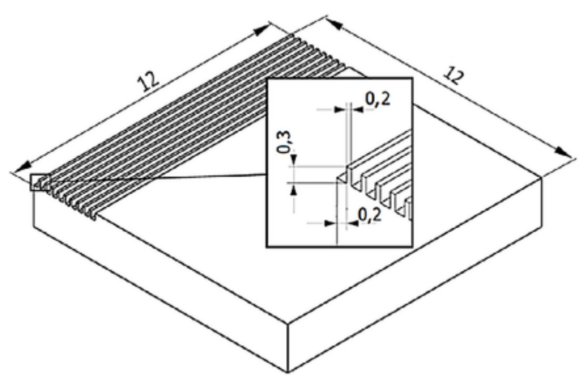


Fig. 4. Design of micro-channel (in mm).

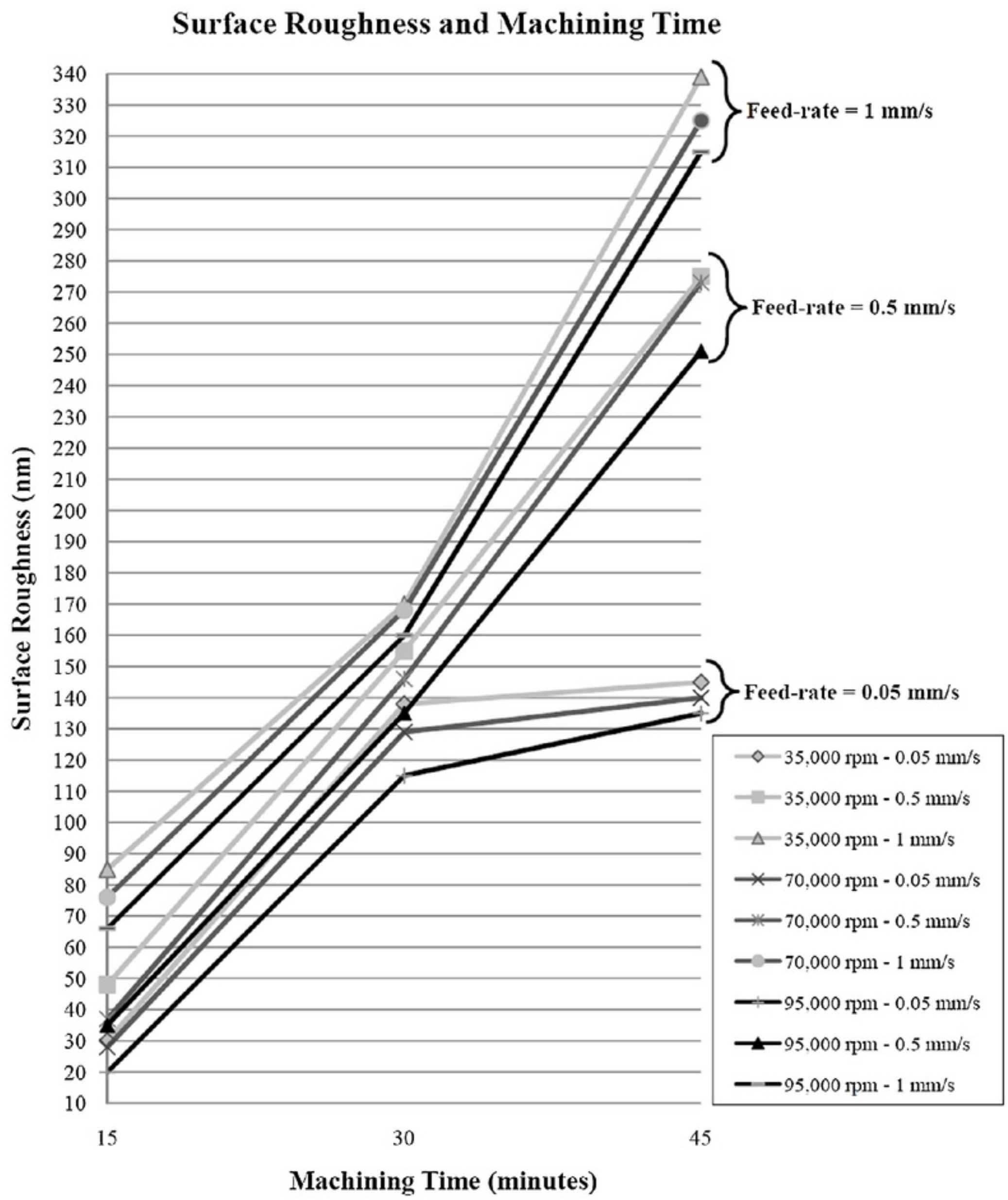


Fig. 5. Comparison of surface roughness and feed-rate in three interval ranges of machining time.

Table 1
Variable factor levels and result of surface roughness measurement.

Spindle speed, n (rpm)	Feed-rate, f (mm/s)								
	0.05 Machining time, t (min)			0.5 Machining time, t (min)			1 Machining time, t (min)		
	15	30	45	15	30	45	15	30	45
35,000	30	138	145	48	155	275	85	170	399
70,000	28	129	140	37	146	273	76	168	325
95,000	20	115	139	35	135	251	66	160	315

to discover the relationship among spindle speed (n), feed-rate (f) and machining time (t) on surface roughness (R_a). The burr formation was observed for each type of burr. The observation was performed by noticing its presence and by comparing burrs length and width.

2. Experimental setup

The experiment was performed by using a miniaturized 5-axis micro-milling machine as shown in Fig. 2. The micro-milling machine has 5-axis of movement, three linear axes of XYZ and two rotational axes A & C. However, only three linear axes, XYZ, were used in the experiment. Fig. 2(b) shows the controller of the micro-milling machine from Suruga Seiki. Three units of DS102/112 were used to control the direction, speed and the distance of each motor movement. Axis movement was powered by stepper motor stage with 1 µm motion resolution and 5 µm positioning accuracy for each axis. The stroke of each linear axes XYZ is 20 mm, 20 mm and 30 mm, respectively.

The workpiece material used in the experiment was AA1100, which is known as a ductile enough material to machine and superior corrosion resistance thus used in quite variety of many industrial applications. Carbides tools are recommended for cutting aluminum alloy because of their superior abrasion resistance and ability to perform a high speed cutting. The chosen cutting tool used in the experiment was solid carbide coated with Mega-T (SECO) that has two flutes and diameter of 0.2 mm. Fig. 3 shows the tool specification used in the experiments.

In the experiments, micro-channels were produced through slot milling operations on workpieces with 12 mm × 12 mm × 3 mm in

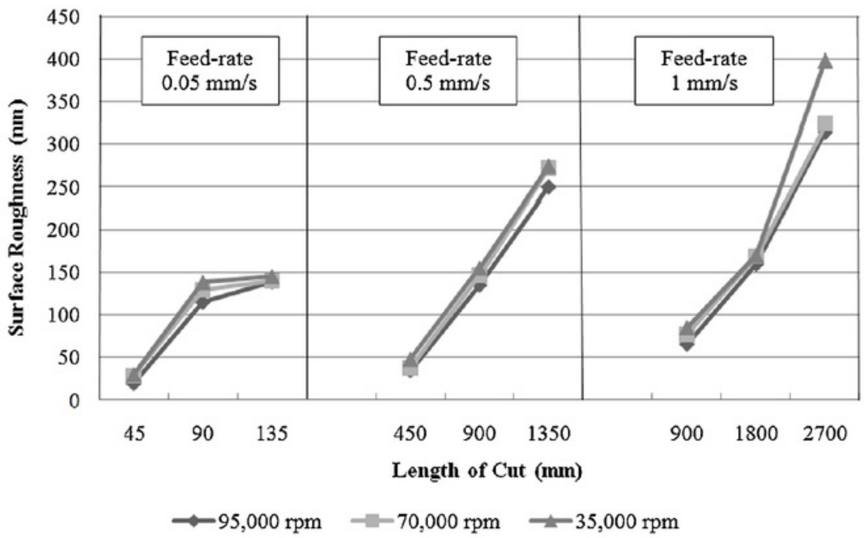


Fig. 6. Comparison of surface roughness and length of cut.

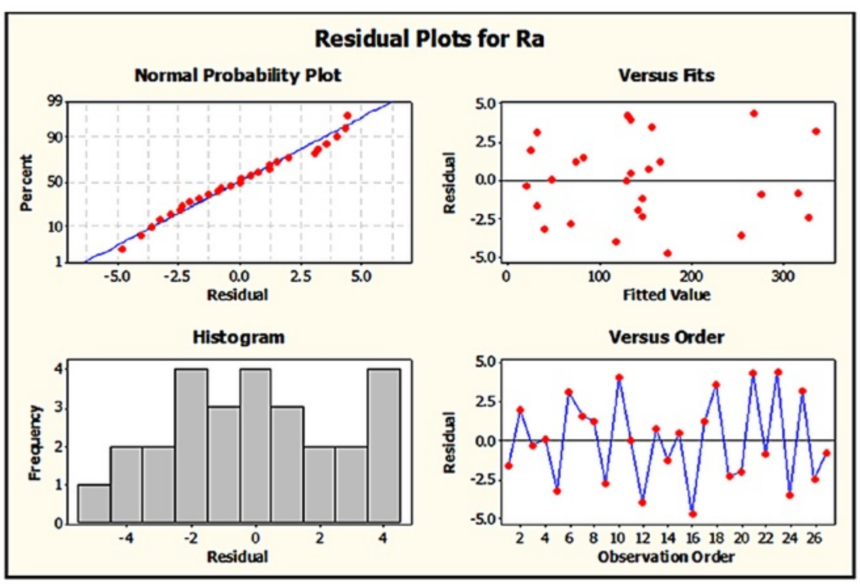


Fig. 7. Residual plots for surface roughness (R_a).

dimension. Slot milling operation produced a channel width equal to the diameter of the cutting tool. Depth per cut for all cutting process was defined constant at 10 μm. Depth of each channel was diverse, depending on variation of specified machining time and feed-rate. The channel depth was calculated based on length of cut (L) correspond to machining time and feed-rate. Afterwards, length of cut was divided by length of workpiece (12 mm) to obtain number of cutting layer. Due to the tool geometry, maximum depth of the channel was 0.3 mm which means 30 cutting layers. If the length of cut required more than 30 cutting layers, then the cutting process would be continued to next micro-channel. The distance of micro-wall between each channel was defined as 0.2 mm and with aspect ratio of 1.5. Fig. 4 shows the design of the micro-channel.

The tool was rotated by an ultra-high speed air turbine spindle HTS1501S-M2040 with rotating capability up to 150,000 rpm. A tachometer panel and an optical sensor from Monarch Bench instrument were used to measure the spindle speed and feed-back data to maintain the desired spindle speed. The tachometer has capability to measure the rotational speed up to 250,000 rpm. The PM Remote data acquisition software was used to store the data of spindle speed during the cutting process.

The surface roughness was measured using Surfcom 2900SD. The measurement settings were 0.08 mm cutoff, 0.08 mm S length, 0.16 E length and 0.2 mm/s of speed. Two digital microscopes were used for positioning and monitoring the stylus during the measurement. Each measuring position was repeated three times.

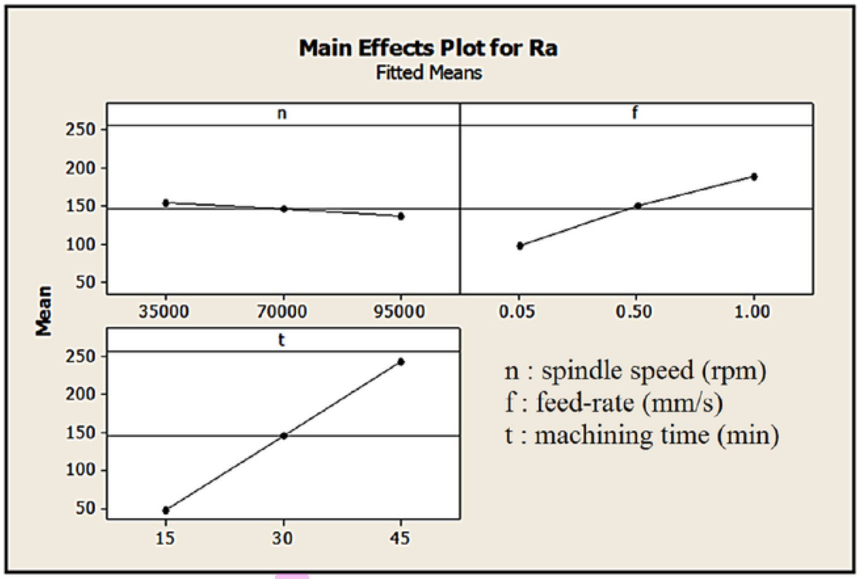


Fig. 8. Main effect plot for roughness (R_a).

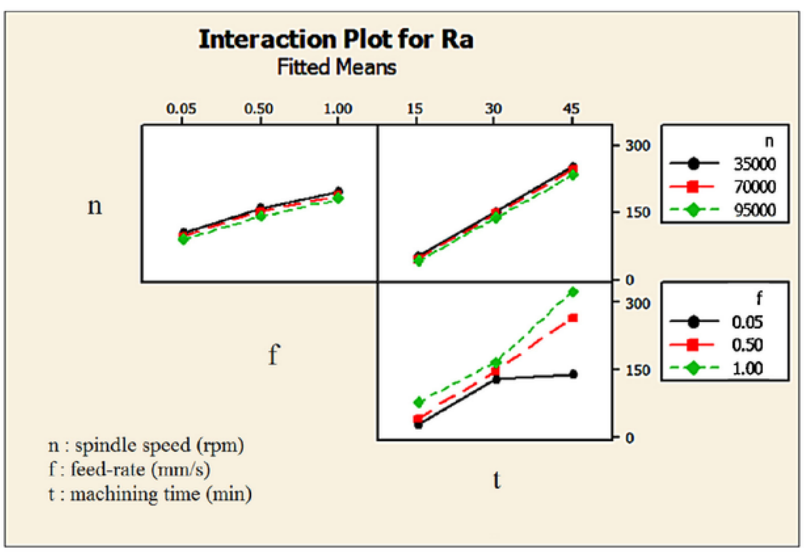


Fig. 9. Interaction plot for roughness (R_a).

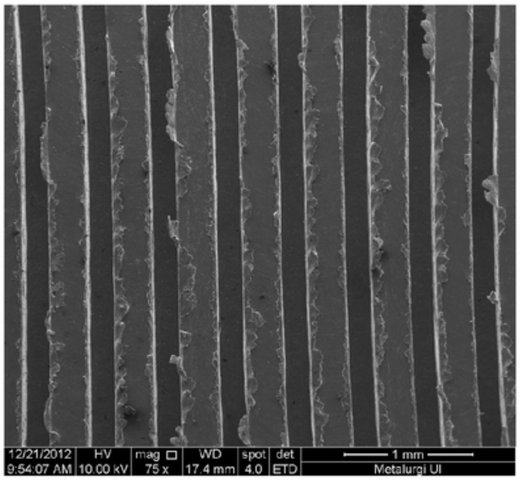


Fig. 10. Top burr formations at top of the micro-channel.

Three level cutting parameters of spindle speeds (n), feed-rates (f) and machining time (t) were assigned in the experiment. Spindle speed, feed-rate and machining time variation are shown in Table 1. Depth of cut for all cutting process was defined constant at 10 μm. Before performing the cutting process, the work pieces were smoothed by facing operations using a 2 mm diameter with 2-flutes TiC uncoated tools.

The experiment was designed by 3^3 full factorial design of experiment through 27 runs (27 cutting experiments performed). Statistical method of linear regression and Analysis of Variance (ANOVA) were used to analyze the result of the experiment. They were used to determine the relationship among those parameters and to determine which parameters most affecting surface roughness. The burr formation was analyzed by using Scanning Electron Microscope (SEM) with FEI Inspect F50.

3. Result and discussion

3.1. Surface roughness

Surface roughness is a measured parameter that can be used to analyze the quality of the micro-machining process. Statistical analysis of ANOVA was used to find the relationship of spindle-speed (n), feed-rate (f) and machining time (t) to the surface roughness. Table 1 shows the measured surface roughness (R_a) of the experiment.

In order to give a more understanding on the relation between machining time and surface roughness, the results of experiments are also summarized in Figs. 5 and 6, and Table 2.

Fig. 5 illustrates that the surface roughness increases along with machining time. It is clearly seen from the figure that, with the same spindle speed, lower feed rate produces lower surface roughness. Different machining time with different feed rate consequently result in different length of cut. This relationship is summarized in Table 2. In practice, micro part needs to be machined within a specified cut length and specified surface quality. When the total cut length to produce a part is known, then Table 2 and Fig. 6 show which cutting parameters would cover specified surface roughness. When the surface roughness is made as a constrained, e.g. less than 100 nm, and the total cut length is, e.g. 200 mm, then feed-rate of 0.5 and 1 mm/s can be used without bothering to change the tool. Furthermore, to have more productive machining, feed rate of 1 mm/s is the best choice since it can produce 4 parts within the required surface quality.

It is clearly seen from Table 2 and Fig. 6 that within the same machining time, a higher feed-rate, that consequently giving more productive machining since produce more cut length (20 times longer), would not degrading surface quality significantly. In other words, longer cut length can be obtained and thus more parts can be produced with higher feed rate without sacrificing surface quality.

General regression analysis was used to comprehend the relationship of cutting parameters spindle speed, feed-rate and machining time with respect to surface roughness. The surface roughness data was calculated using statistical software. The observed value (F) of the experiment is 70.309 while, the critical value at significant level 0.05 taken from table of percentage points of F distribution, is $F_{0.05,6,20} = 2.6$. The critical value $F_{0.05,6,20} = 2.6$ is less than the observed value $F = 70.309$ while, the P value from data calculation is 0.003, which is less than the significant level of 0.05. Both value F and P; give a statistical evidence to reject the null hypothesis. It implies that at least one of the independent parameters of spindle speed (n), feed-rate (f), and machining time (t) contribute significantly to the model.

The model adequacy checking was examined based on the regular residual plot of R_a result of a statically software calculation as seen in Fig. 7. It consists of plots of normal probability, residual versus fitted values, residual frequency and residuals in time sequence. The residual plots show that the residuals are structure-less, contain no obvious patterns and unrelated to any other variable. It can be concluded that the model from the experiment is satisfying.

The simplest way to determine the most influential parameters to the surface roughness is by obtaining the idea from the Main Effect Plot for Ra, as shown in Fig. 8. The plot shows that good surface quality can be achieved by increasing the spindle speed and decreasing the feed-rate. Moreover, the plot also shows that machining time is the most influential parameters on surface roughness due to tool wear effect.

The t-value is used in order to examine significant contribution of independent variables to the surface roughness. The critical

Table 2
Range of surface roughness and cutting parameters.

Machining time (min)	Cutting parameter[a] (feed-rate, mm/s)	Total length of cut (mm)	Surface quality (R_a, nm)		
45	0.05	135	139	140	145
	0.5	1350	251	273	275
	1	2700	315	325	399
30	0.05	90	115	129	138
	0.5	900	135	146	155
	1	1800	160	168	170
15	0.05	45	20	28	30
	0.5	450	35	37	48
	1	900	66	76	85

[a] Depth per cut = 10 μm.

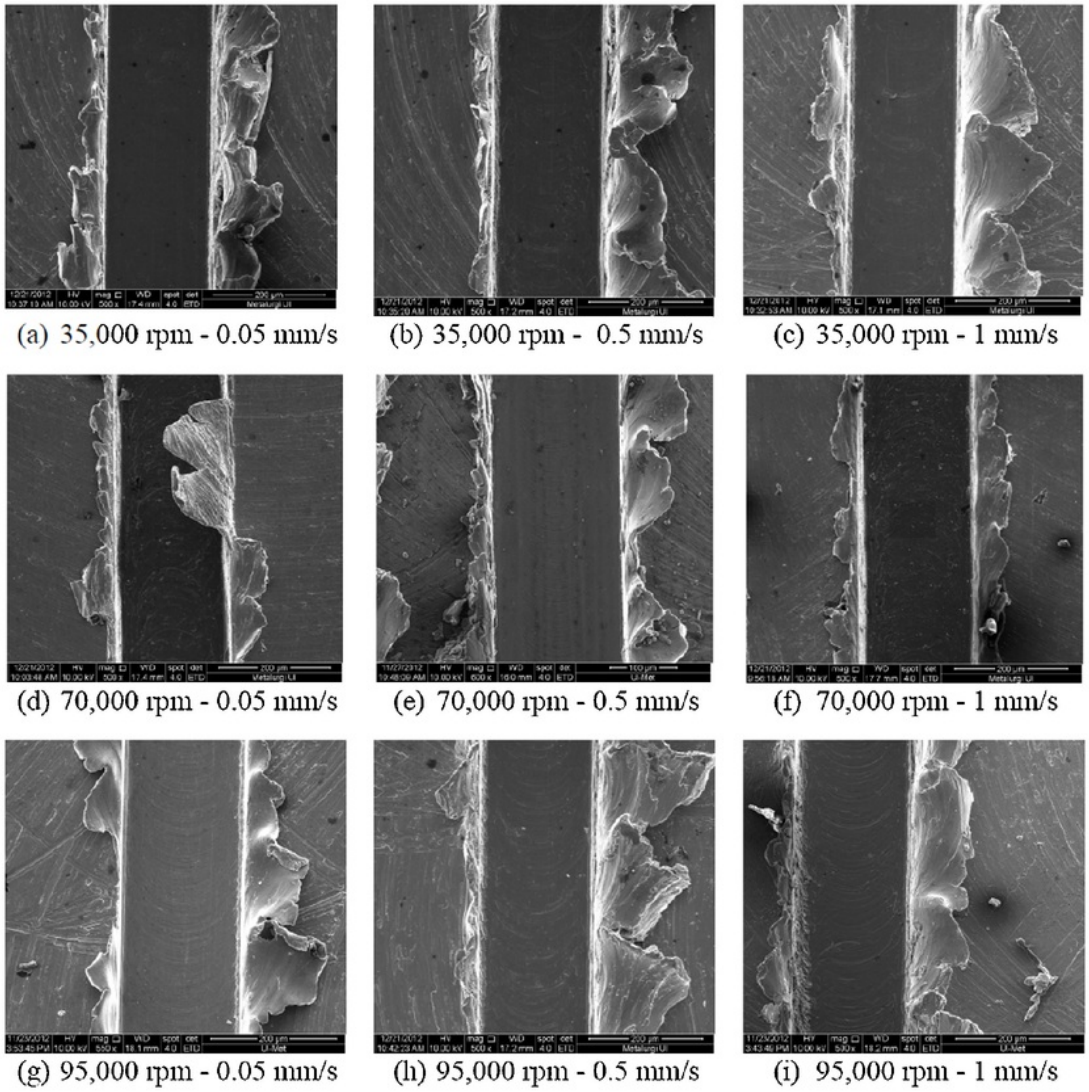


Fig. 11. Top view of the micro-channel for each cutting parameter after 45 min.

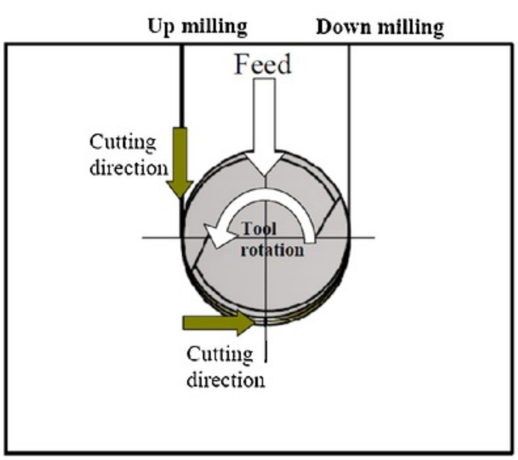


Fig. 12. Slot milling.

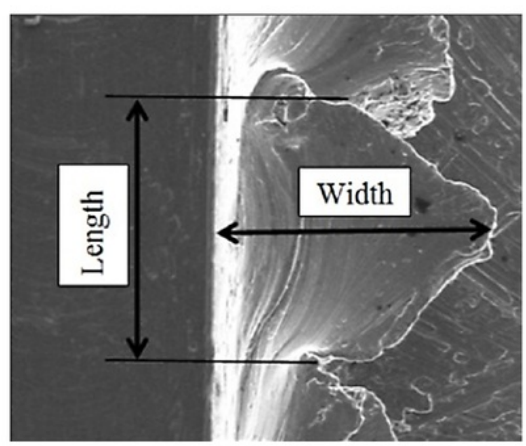


Fig. 13. Length and width of burr.

t-value obtained from table of t-value $t_{0.025,20}$ is 2.086 [17]. The result of absolute t-value calculation using A statically software for each cutting parameters spindle speed (n), feed-rate (f) and machining time (t) is 1.1175, 6.0867 and 13.1381, respectively. It can be concluded that feed-rate (f) and machining time (t) contribute significantly to the response of Surface Roughness (R_a), because the t-value of feed-rate and machining time is greater than the critical t-value $t_{0.025,20} = 2.086$.

The interaction between each parameter was examined by observing the interaction plot for R_a, as shown in Fig. 9. It shows that there are interactions among spindle speed with feed-rate and also spindle speed with machining time, since the lines are far from being parallel.

3.2. Burr formation

In micro-milling process, burr formation greatly affects the work piece quality due to the size of burr could be approaching the size of cutting tool diameter. By using Photos SEM, it clearly visible that burr is formed on the micro-channel surfaces. There were four types of burr occurred which were top burr, entrance burr, side burr, bottom burr, and exit burr.

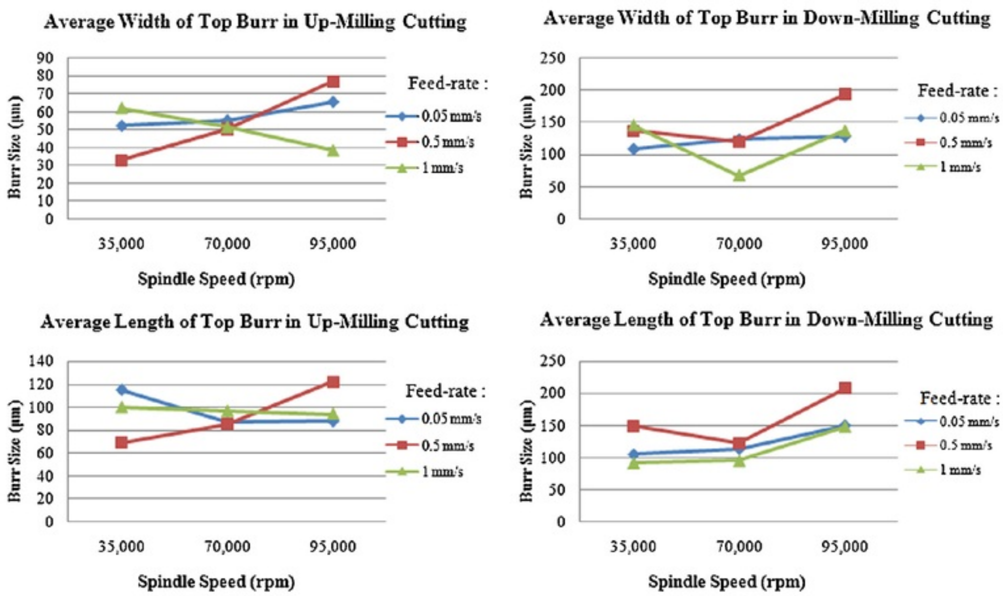


Fig. 14. Average top burr size for three ranges of spindle speed and feed-rate.

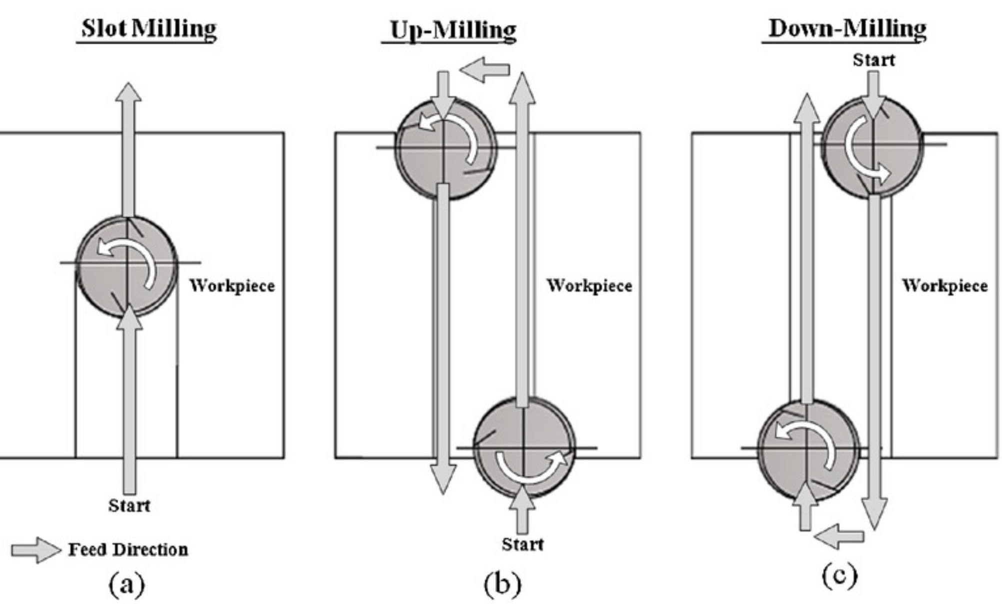


Fig. 15. Tool movement to perform (a) slot milling, (b) up-milling and (c) down-milling.

Table 3
Average top burr size in slot cutting.

Spindle speed (rpm)	Feed-rate = 0.05 mm/s		Feed-rate = 0.5 mm/s		Feed-rate = 1 mm/s	
	Width	Length	Width	Length	Width	Length
Up-milling burr size (μm)						
35,000	52.29	115.1	33.22	69.35	62.36	100.08
70,000	55.4	87.3	50.5	85.3	51.81	96.75
95,000	65.7	88.4	76.93	122.4	38.47	94.2
Down-milling burr size (μm)						
35,000	109.35	105.5	137.5	148.6	146	92.95
70,000	123.6	114.2	120.3	122.5	67.62	96.16
95,000	128.2	151	194.4	207.5	137.5	148.6

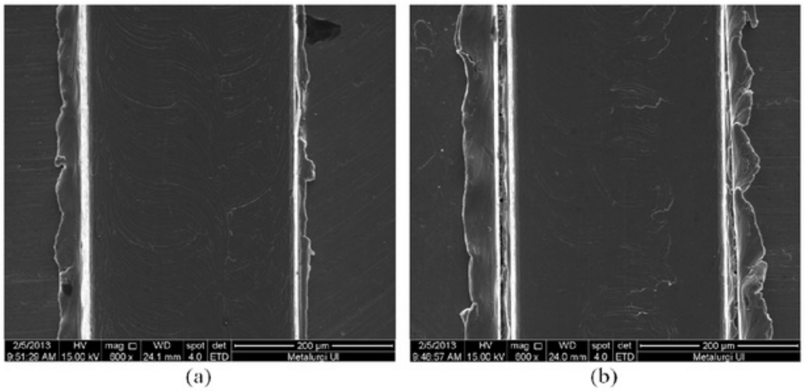


Fig. 16. (a) Work piece cut by using up-milling cutting strategy and (b) work piece cut by using down-milling cutting strategy; after 15 min.

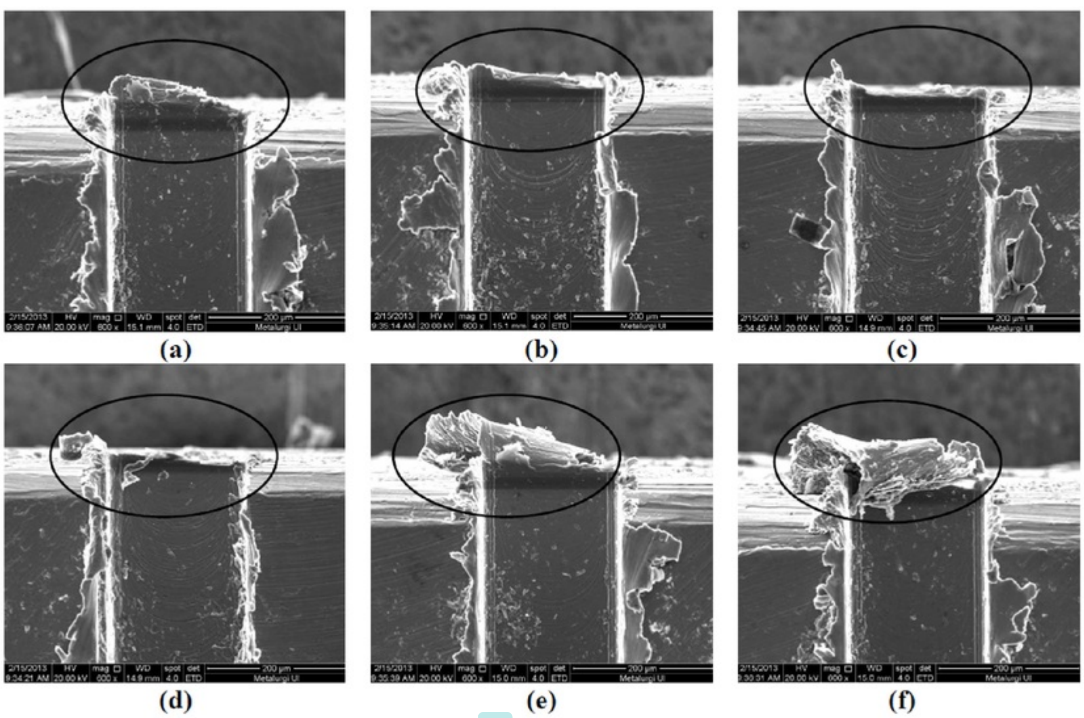


Fig. 17. Entrance burr, approximately (a) 36 s, (b) 72 s, (c) 108 s, (d) 144 s, (e) 180 s and (f) 216 s.

3.2.1. Top burr formation

Burrs that are formed on top of the work piece surface is called top burr. Fig. 10 shows the top burrs occurrence on the micro-channels surface. It is noticeable that the work piece quality becomes poor due to the burrs. In macro-milling, burr does not look as clear as in micro-milling and sometimes can be ignored. However, the burr size in micro-channel is almost equal to the channel width and hence it becomes very disruptive.

The experimental results indicate that cutting parameters affect the top burr formation. Fig. 11 shows photos of top burr formations for each pairs of cutting parameters. From these images, it can be concluded that pairs of spindle speed and feed-rate at 35,000 rpm – 0.05 mm/s, 70,000 rpm – 0.5 mm/s, 70,000 rpm – 0.5 mm/s and 95,000 rpm – 1 mm/s produce minimum burrs.

Further evidence from the pictures shows that top burr formations on each side of the micro-channel are different. It is widely understood that, when micro channel width is the same as tool diameter, there are two different cutting directions taking place on each side of the micro-channel, up-milling and down-milling, as shown in Fig. 12. On the side of Up-milling cutting, the cutting direction is parallel to the feed direction, while on the side of down-milling, the cutting direction is opposite to the feed direction. It appears that on slot cutting, the burrs are mostly formed on the side of down-milling.

The burr size for all pairs of cutting parameters was measured and averaged. The burr width and length were measured as shown in Fig. 13.The measurement was performed in the range of +1 mm and −1 mm within 45 min of machining time for each cutting parameters. The average size of burr is shown in Table 3. It is found that the average burr size for the entire micro-channel is uneven and has the tendency to grow along the cutting process of the micro-channel. However, the burr dissipated in some sections of the micro-channel. It occurred due to the detached of the build-up edge from the cutting edge.

Based on Fig. 14, it can be seen that there is no specific relation and pattern among spindle speed, feed-rate and average burr size. The best cutting parameters selection to produce minimum burrs can only be identified by experimental result.

Further cutting experiments were performed to understand the burr formation characteristics for each machining strategy, up-milling and down-milling cutting. End-mill solid carbide coated tools with 0.2 mm in diameter and work piece material AA1100 used in these experiments were the same as the previous experiment. Spindle speed of 70,000 rpm and feed-rate of 1 mm/s were assigned for the cutting parameter. The final width of the micro-channels was bigger than the tool diameter, which was 0.28 mm.

Since the direction of spindle rotation could not be changed, the tool movement was assigned as shown in Fig. 15 to obtain up-milling and down-milling cutting. First, the slot cutting was performed to make a space for further cutting. Start point of the tool movement would determine the type of cutting strategy.

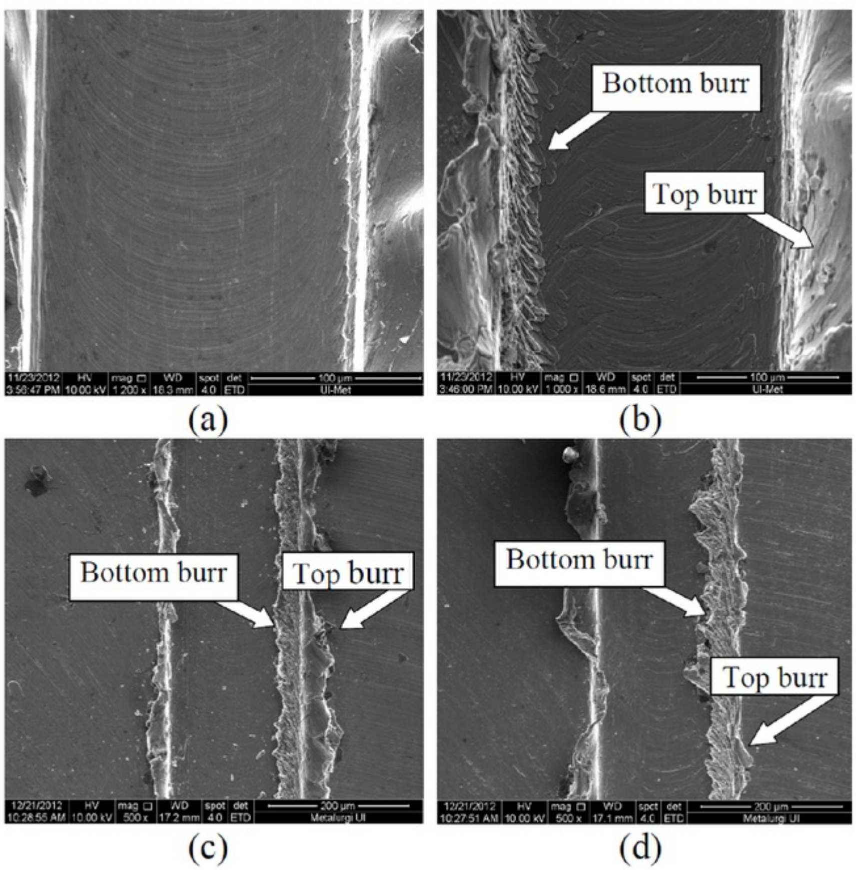


Fig. 18. (a) Machined surface of a new tool cut with cutting parameters of 90,000 rpm in spindle speed, 1 mm/s in feed-rate, (b) more top burrs were formed than bottom burrs, (c) The top burrs approximately equal to the bottom burrs and (d) more bottom burrs were formed than top burrs.

Result of up-milling and down-milling cutting strategy is presented in Fig. 16. It shows that down-milling cutting strategy produces bigger and wavier burrs compare to up-milling cutting strategy. Thus, this confirms the result shows in Table 3.

3.2.2. Entrance burr formation

The entrance burr was formed on the entrance side of the micro-channels as shown in Fig. 17. The entrance burr grew as machining time increased. It appears that entrance burr formation is related to the tool wear.

3.2.3. Bottom burr formation

The bottom burr could occur on both sides of the micro-channel, whether on up-milling side of cutting or down-milling side of cutting. New and sharp tool produced channels with 'almost' free from bottom burr as shown in Fig. 18(a). However, more bottom burrs were formed as a result of the cutting tool damaged due to the increasing of machining time; Fig. 18(b) and (c). The bottom burr could become larger compared to top burr, Fig. 18(d) as the tool continues to wear.

Fig. 19 shows the bottom surface of the micro-channel. The channel depth was 0.3 mm, determined based on the flute length of

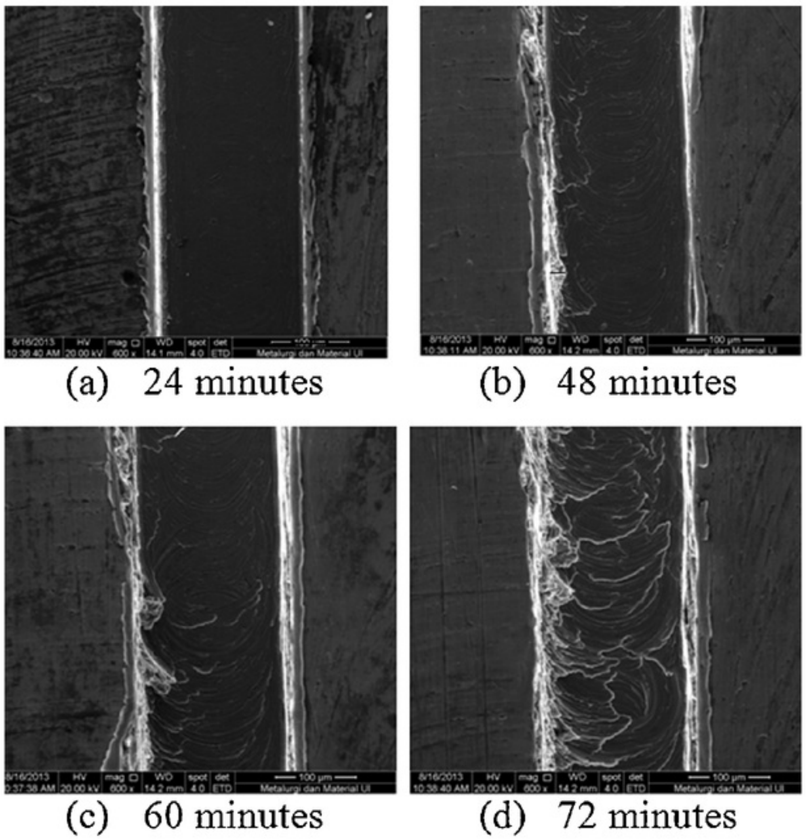


Fig. 19. Bottom burr growth in interval of time.

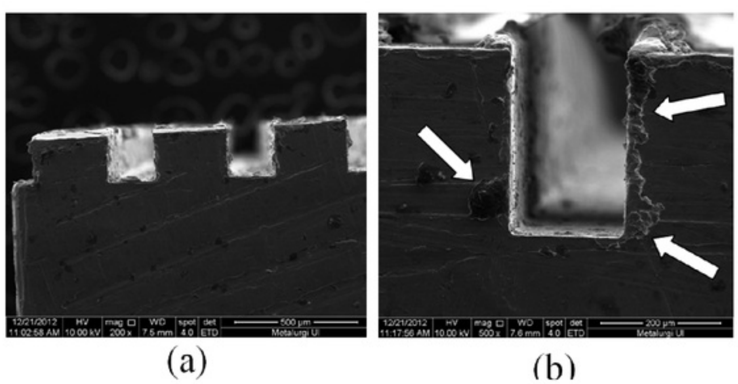


Fig. 20. (a) Side view of the micro-channel and (b) exit side burr occurrence at side of the micro-channel.

the cutting tool. The micro-channel was produced with 0.5 mm/s of feed-rate, 70,000 rpm of spindle speed and 0.01 mm depth of cut. The time required to complete a single micro-channel was 12 min. The surface condition in Fig. 19 was taken close to the end side of the micro-channel.

It was hard to define the bottom burr size since the burrs were spread on the bottom surface in semi-circular pattern following the tool rotation direction. The burr rapidly grew as the tool started to wear and the machining process was dominated by rubbing instead of cutting.

3.2.4. Exit burr formation

Exit burr with wavy shape was formed on both exit sides of the micro-channel as shown in Fig. 20. Although both sides were cut with different cutting strategy, it resulted in the same burr's shape and size evenly. Meanwhile, fewer burrs were seen on the exit bottom side of the micro-channel.

The micro-channels were produced by multi layer cutting with 10 μm depth per cut. The exit burrs were continuously formed at each level of depth per cut and increased as the depth and tools wear escalating.

In order to view the surface quality of the micro-channel walls, the last cut of micro-channel was placed next to the outer side of the work piece, as shown in Fig. 21. The picture shows that the wall and the micro-channel are no longer in a rectangular shape. This might occur due to the cutting tool deformation as a result of the twisting chip and the build-up edge on the tool surface.

3.2.5. Effect of tool wear on burr formation

Some literatures have explained about burr formation correspond to cutting parameters. However, there is inadequate knowledge about machining time related to burr formation. In this section, it is shown that machining time is the most significant cutting parameter effecting burr formation. Figs. 22 and 23 show a new tool condition before machining and the flank wear that occurred after 15 min of machining process, respectively. A comparison among three ranges of machining time and related tool condition is expressed in Fig. 24. Fig. 24(a) shows that after 15 min, the cutting edge started to wear. The wear continued to grow until there was no trace of cutting edge in 30 min of machining time. In Fig. 24(b), it can be seen that the tool edge was chipping after 45 min of cutting process. Edge chipping of the cutting tool proved that there was a periodic break-off of the BUE.

When the tool wore, the top burr size increased on both side of the micro-channel. Although the burr size was varied, it has the tendency to become wider. As it can be seen in Fig. 24(c) bottom burr was also formed on the bottom surface of the micro-channel after 45 min. It occurred due to the fracture on the cutting edge.

The average size of top burr during three ranges of machining time for each cutting strategy, up-milling and down-milling, was investigated in other experiment and the result is shown in Fig. 25. The burr size grows as the machining time for both up-milling and down-milling cutting increases.

The selection of cutting parameters would affect the tool condition. Fig. 26 shows photos of the cutting tool condition after 45 min with different cutting parameters. Low feed-rate would result in a better surface roughness but it would lead to continuous chip formation. The chips were wrapping and twisting around the tool and

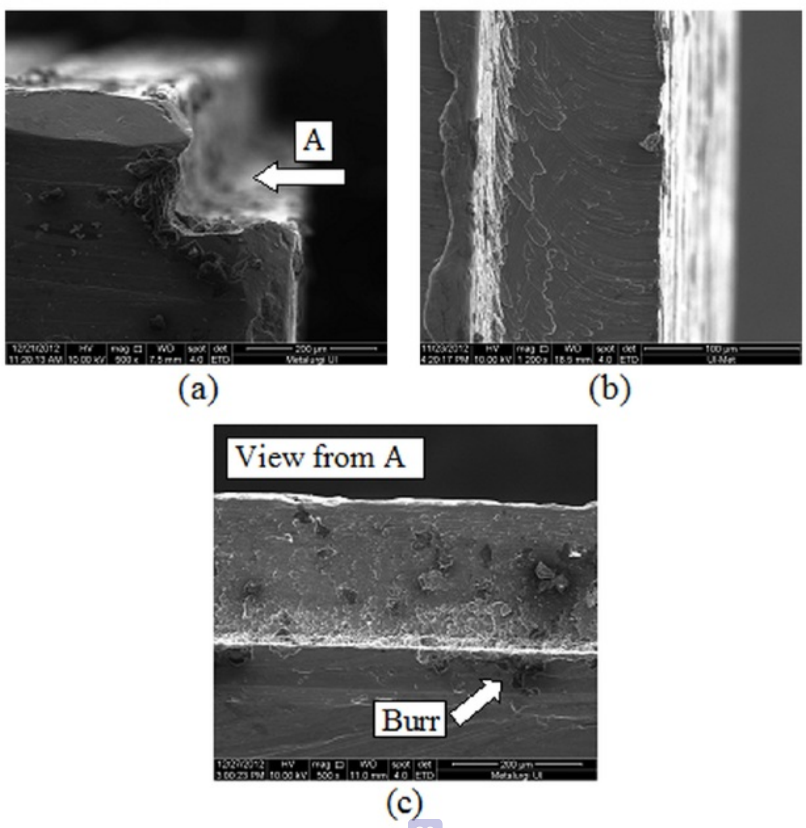


Fig. 21. The half cut of a micro-channel (a) front view, (b) top view and (c) side view.

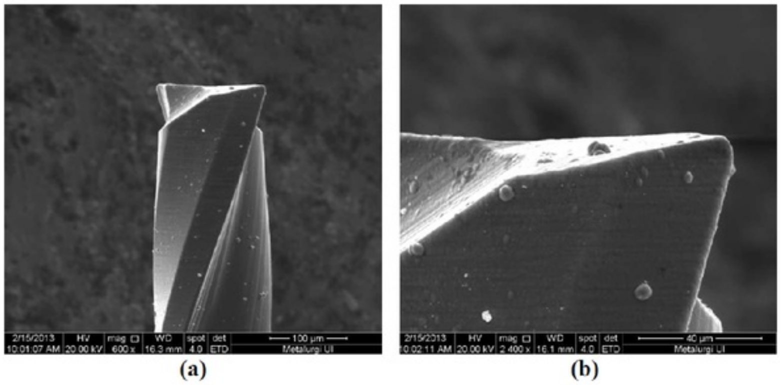


Fig. 22. New tool.

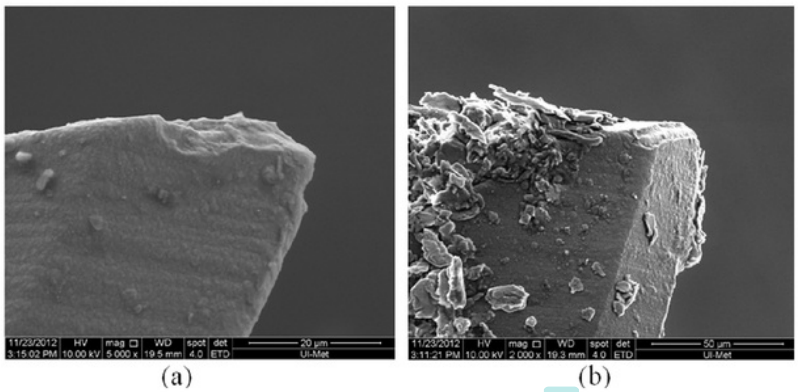


Fig. 23. The flanks wear occurred on a cutting edge after 15 min of machining process; (a) 70,000 rpm – 0.5 mm/s and (b) 70,000 rpm – 0.05 mm/s.

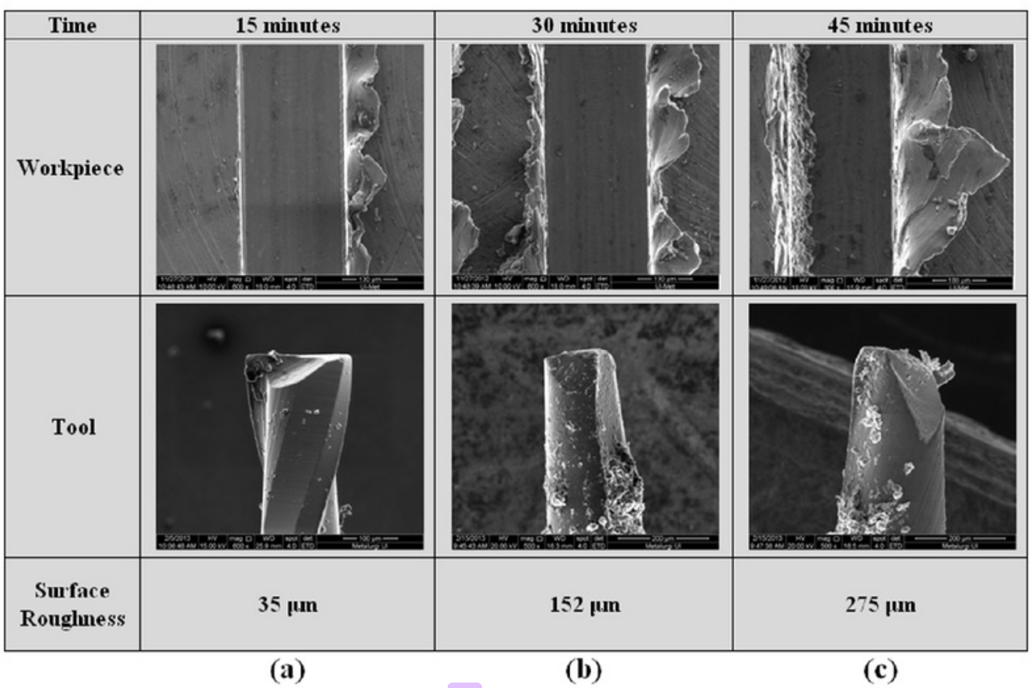
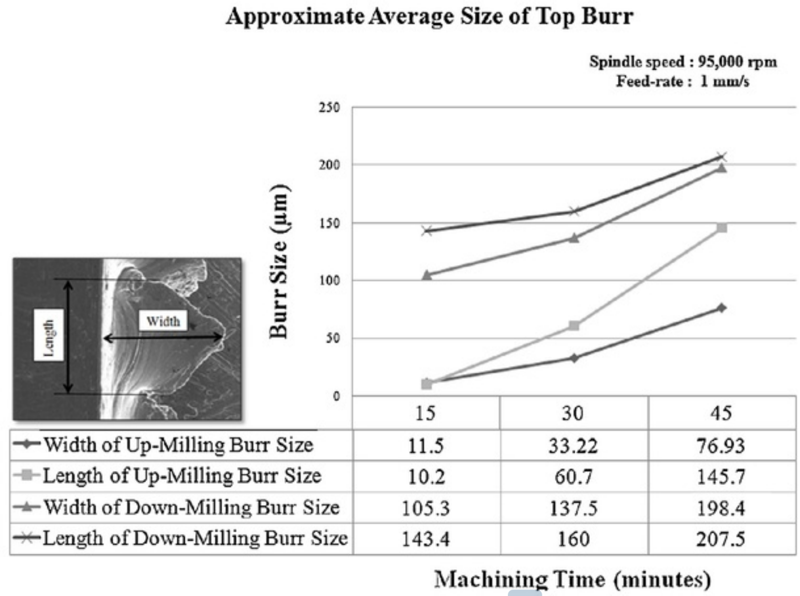
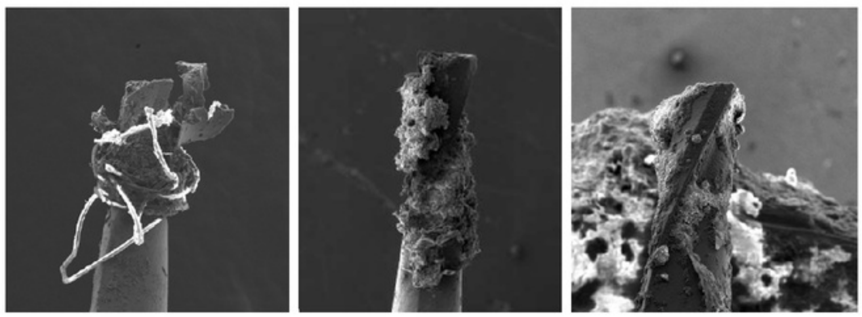


Fig. 24. Micro-channel produced with 95,000 rpm spindle speed and 1 mm/s feed-rate and the tools condition (a) after 15 min; (b) after 30 min; (c) after 45 min.



	15	30	45
Width of Up-Milling Burr Size	11.5	33.22	76.93
Length of Up-Milling Burr Size	10.2	60.7	145.7
Width of Down-Milling Burr Size	105.3	137.5	198.4
Length of Down-Milling Burr Size	143.4	160	207.5

Fig. 25. The average size of top burr in slot cutting on each up-milling and down-milling.

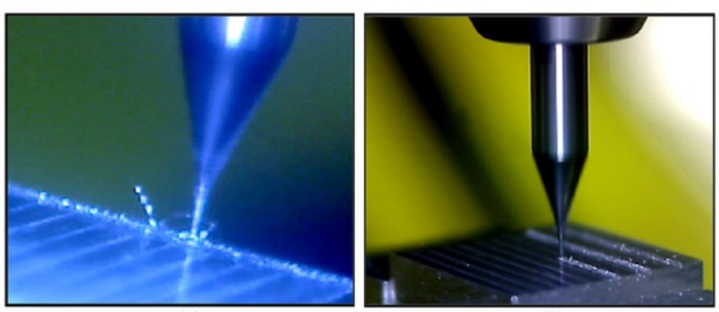


(a) (b) (c)

Fig. 26. The real cutting tools condition without cleaning after 45 min with spindle speed of 70,000 rpm (a) feed-rate of 0.05 mm/s, (b) feed-rate of 0.5 mm/s and (c) feed-rate 1 mm/s.

would interfere with subsequent cutting process. The continuous chip changed the tool geometry and affected the channel shape. Moreover, the continuous chips had the possibility to enter the micro-channel and crushed by the tool on the next cutting movement. This continuous chip occurred while the cutting process with feed-rate of 0.05 mm/s and spindle speed of 70,000 rpm was performed, as shown in Figs. 26(a) and 27(a).

Cutting process with 0.5 mm/s of feed-rate and 70,000 rpm of spindle speed, formed a build-up edge (BUE) on the cutting tool surface, as shown in Fig. 26(b). Although thin layer of BUE could



(a) (b)

Fig. 27. (a) Continuous chip as result of cutting process at feed-rate of 0.05 mm/s and (b) cutting process at feed-rate of 1 mm/s.

reduce tool wear, it would change the tool geometry, affecting the micro-channel rectangular shape and creating a possibility to fall apart into the micro-channel which would interfere with the cutting process.

Fig. 26(c) shows the picture of the cutting tool using 1 mm/s of feed-rate and 70,000 rpm of spindle speed. The cutting tool seems to be cleaner than the others. However, if the analysis was made by comparing the value of surface roughness, the feed-rate of 1 mm/s would have the highest surface roughness because it wore quicker than others.

4. Conclusions

This experimental work has discovered the behavior of cutting parameters and machining time with respect to surface roughness and burr formation in micro-milling operation. The micro-milling process was performed by three variations of feed-rate and spindle speed in three intervals of machining time. Both surface roughness and burr formation were analyzed. The tool condition was compared to get an idea of wear influence in micro-tool.

By statistical method, it is found that feed-rate (*f*) and machining time (*t*) contribute significantly to surface roughness. Within the same machining time, a higher feed-rate, that consequently giving more productive machining since produce more cut length (20 times longer), would not degrading surface quality and tool life significantly. Furthermore, the choice in cutting parameters would not merely depend on the specified surface roughness but can also be related to how many parts can be produced.

Top burr, bottom burr, entrance side burr and exit side burr were formed in slot milling operation. Fewer top burrs were formed on up-milling side of the micro-channel. Bottom burr occurred as the tool began to wear and became larger than the top burr as the tool wear increased or the tool cracked. Tool wears due to machining time is the most influential factor on burr formation.

Lower feed-rate would produce smoother surface. However, it could produce continuous chip and be inefficient in terms of time. Continuous chips could enwrap/twist around the tool. Build-up edge (BUE) was also possible to be formed on the tool surface. Continuous chip and BUE changed the tool geometry and affected the micro-channel dimension during periods of machining time. After 45 min of cutting process, the shape of the micro-channel was no longer rectangular due to the tools geometric transformation. Furthermore, the chip may enter the micro-channel and interferes the cutting process.

In order to produce a burr-free product, it is recommended to perform the machining process by using up-milling cutting strategy. Appropriate selection of cutting parameters can minimize the burr formation.

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