SEMARAK ILMU
PUBLISHING
202103268166(003316878-P)

Journal of Advanced Research in
Applied Mechanics

Journal homepage:
https://semarakilmu.com.my/journals/index.php/appl_mech/index
ISSN: 2289-7895

Effect of Machining Parameters on Micro-Burrs Formation of Aluminium Puncher using High-Speed Machining Process

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ARTICLE INFO

Article history:
Received 20 November 2023
Received in revised form 16 January 2024
Accepted 30 January 2024
Available online 22 March 2024

Keywords:
Micro-burr formation; micro-milling; high-speed machining

ABSTRACT

Micro-burrs are small protrusions or imperfections that can form on the surface of a machined part during the machining process, which may lead to reduced product quality, decreased performance, and increased wear and tear. The formation of micro-burrs on the puncher can adversely affect the accuracy and surface finish of replicated microchannel parts in secondary processes like hot embossing. The objective of this study is to investigate the effect of machining parameters on micro-burr formation in the Y-type Al6061-T6 microchannel puncher. The machining parameters include spindle speed, feed rate, and depth of cut in twenty experimental works designed using the Central Composite Design (CCD) approach for machining with uncoated solid carbide end milling tools. Results indicate that the top micro-burr formation in the Y-type Al6061-T6 microchannel puncher is significantly influenced by feed rates compared to spindle speed and depth of cut. The minimum burr width occurs at a feed rate of 30 mm/min, while maximum burr values are observed at 150 mm/min. The best parameter combination identified in this study is a spindle speed of 14000 r/min, a feed rate of 90 mm/min, and a moderate depth of cut of 50 µm. This knowledge can be applied to selecting appropriate cutting parameters when planning microchannel puncher fabrication using a high-speed machining process to achieve precision and minimize burr formation.

1. Introduction

A microchannel is a small channel or duct typically measured in micrometers. According to Prakash and Kumar [1], the use of microchannels covers three main categories; biological applications, chemical applications, and electronics and mechanical engineering-related applications. In a comprehensive study by Afzal *et al.,* [2], stated that the microfluidic and biomedical industries are the two main applications of microchannels. Some common applications of microchannels include microfluidic devices, heat exchangers, chemical synthesis, electronics cooling, biomedical devices, energy systems, optical devices, microfabrication, environmental monitoring, radiation

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https://doi.org/10.37934/aram.115.1.4760

detectors, and used in shuttle space as seen in research papers by several authors [1-3]. The versatility of microchannels makes them applicable in a wide range of industries and research fields, contributing to advancements in technology and scientific research.

Microchannel can be created using various techniques. Prakash and Kumar [1] reported that microchannel can be produced by micro-mechanical cutting, wet and dry Etching, Lithography, Embossing and Imprinting, Injection molding, and Laser-evolved Microchannelling. The previous study by Afzal *et al.,* [2], listed several techniques for manufacturing microchannels, including the following; Lab on chip, Micromolding, Electroplating, Injection molding, Ultrasonic machining, Electrochemical Micromachining (EMM), 3D printing, Laser direct writing, Laser micromachining, Micromachining, Laser ablation, Microcontact printing (μCP), Micro Total Analysis System, Rapid Prototyping, Hot Embossing, Etching, Photolithography, Lithography, Micromilling, Excimer laser micromachining, Femtosecond laser bulk micromachining, Lithography, electroplating, and molding (LIGA, from the German lithographie, galvanoformung, abformung), and Modified techniques combining The aforementioned. Each technique has its advantages and disadvantages. The selection of microchannel manufacturing techniques should take into account factors such as the desired dimensional accuracy, material, main area of application, manufacturing cost, time consumption, and similar considerations.

Focusing on a microchannel fabrication technique by using micromilling, its advantages have been reported by several authors. Raman and Wadke [4], reported that micromilling can produce intricate three-dimensional microfeatures with exceptional dimensional accuracy. Additionally, a study by Mijušković́c and Cica [5], recorded its efficiency in various materials using sub-millimeter micro-mills with diverse coatings. This is supported by a study from Prakash and Kumar [1], which reported that the advantages of micromilling include producing highly accurate machining results, good surface finish, form accuracy, and the capability to operate at high machining speeds. However, machining micro-sized features are challenging, especially in obtaining the required accuracy and surface quality, in addition to other problems such as burr formation.

A burr is a rough or raised area on the surface of a material that can result from cutting or machining processes. It can occur on different materials, including wood, plastics, and metals, and may affect the quality of the final product or component. In contrast, micro-burrs are extremely small burrs, commonly seen in precision machining and microfabrication processes. If not removed properly, these tiny burrs can cause harm to delicate components, decrease performance, and hinder part assembly. Burr formation on micro-sized cuts is more critical and should be avoided. This avoids the need for secondary processes such as deburring that costly, time-consuming, and non-value-added process as reported by Kiswanto *et al.,*[6]. The process of deburring techniques for macro-sized features is not the same for micro-sized features because it will cause dimensional errors and residual stress to the component as seen in research papers by several authors [7-9].

During the micro-milling process, the contact action between the cutting tool and the material plays an important role in the material removal process. This includes rubbing, plowing, and elastic deformation action increasing surface roughness and significant burr formation along the cutting path as reported by L. Chen *et al.,*[10]. Therefore, surface roughness and burr formation are commonly employed as indicators to determine the appropriate machining parameters. The three main and often used machining parameters to study burr formation in machining are feed rates, depth of cut, and cutting speeds. However, some other parameters and factors are studied apart from the three parameters such as the number of cutting tool flutes, cutting condition, size of cutting tool, type of cutting tool coating, toolpath strategy, and others. Gillespie and Blotter [11] observed that the size of burrs produced can be minimized significantly by choosing appropriate machining parameters that consist of workpiece material, tool geometry, tool wear, tool path, and machining parameters.

There are many studies have been conducted to investigate the relationship between the effects of machining parameters on the burrs formation in the micro-milling process. In micro-milling aluminium Al 7075-T6 conducted by Y. Chen *et al.,*[12], that feed rate per tooth has the greatest influence on top burr width and surface roughness, with axial cutting depth and cutting speed having the least impact. High spindle speed, high feed rate, and low depth of cut are the optimum machining parameters for reducing top burrs when micro-milling copper. Kiswanto *et al.,* [6] found no specific relation between spindle speed, feed rate, and burr size in micro-milling Al1100, but identified spindle speed and feed-rate combinations that produced minimum burrs. Other than that, the most significant factor influencing the formation of burrs during machining was the wear of the tool caused by the machining time. Lekkala *et al.,*[13] observed that tool diameter, depth of cut, number of flutes, and the interaction between feed rate and number of flutes have a significant effect on burr height in the micro-milling process. It has been argued that the speed has a relatively insignificant impact on both the thickness and height of the burr. They reported that feed per tooth in the range of 1-3 times edge radius and spindle speed up to 6,366 rpm can reduce burrs in micro-milled Ti-6Al- 4V. Toolpath can also affect burr size, with curved slots producing fewer burrs than straight slots in micro-milling stainless steel (SS304) using a carbide tool. The dimensions of burrs are found to be dependent on the curvature of the tool path, with top burrs showing an increase in values as the curvature increases due to a larger plowing region. Additionally, it has been observed that burr dimensions in straight slots are greater at lower feed values, while circular tool paths result in more burrs at higher feed values as reported by Khan *et al.,*[14]. Overall, uncoated carbide tools generally produced fewer burrs than coated tools in the micro-milling of polycarbonate, and the combination of lower feed rate and higher depth of cut or vice versa can minimize burr formation. It was found by Hanson *et al.,*[15] that both TiN and TiAlN coatings do not help in reducing burr formation. A more significant parameter in reducing bur formation is the combination of feed rate and depth of cut. That contradicts the findings from Hajiahmadi [16] which found that the use of fine-grained tungsten carbide tools with TiAlN coating to cut 316 stainless steel materials can reduce the formation of burrs. The use of a depth of cut below 0.2 mm can reduce the thickness of the burr. However, large burrs will result from the plowing action if a depth of cut higher than 0.2 mm is used. Han *et al.,* [17] analyzed the effect of cutting fluids and the wear of micro-milling tools on surface quality and micro-burr generation. The findings indicated that the formation of burrs and the quality of the surface were highly dependent on both the depth of the groove and the wear of the tool. The application of coolant and low depth of cut to obtain better superficial quality features and a lesser amount of dimensional error in the micro-milling of aluminium, titanium, and stainless steel has been reported by Attanasio *et al.,*[18]. Applying a low depth of cut per pass (2 µm) is crucial in minimizing burr formation in all materials and also affects the accuracy of dimensional measurements, while the use of coolant is critical in achieving better quality surface features that prevent built-up edge formation and material overheating.

From the literature review by several authors [12-18], many studies have been conducted to explore the effects of machining parameters on various aspects in the micro-milling process. However, there is still room for further research on the effects of machining parameters on micro burr formation and other issues arising from the micro-milling process, such as cutting tool wear, the generation of cracks due to mechanical stress, long processing time, and so on. In addition, most previous studies [13,16-19] focused on simple cutting profiles, while the formation of microchannels with complex profiles is rarely reported. For this purpose, this study has been conducted to investigate the effect of cutting parameters on the formation of micro-burr on Y-type microchannel through experiments. The effect of spindle speed, feed rate, and depth of cut on burr formation along straight and curved microchannels has been evaluated and discussed in detail.

2. Methodology

2.1 Experimental Procedure

Different factor levels were used in the experiments to better understand how different parameters, such as spindle speed, depth of cut, and feed rate, affect the surface quality of a Y-type Al6061-T6 microchannel puncher. To prevent any tool wear effects, each set of experiments was carried out with a brand-new end mill. The experiments were designed and analyzed by using Central Composite Design (CCD). Central Composite Design (CCD) is a common statistical tool for optimizing process variables. This present study consists of three factors as independent variables and one response as a dependent variable as shown in Table 1. For a fabrication process, the roughing operation uses a Ø4.0 mm uncoated solid carbide end mill tool except for the generation of the microchannel which was created by a Ø2.0 mm uncoated solid carbide end mill tool. The specifications of the tool geometry are presented in Table 2. The Y-type Al6061-T6 microchannel puncher was machined using a precision five-axis DMG DMU-60 evo CNC milling machine with a vertical spindle using a Siemens 840D controller. The spindle of this machine can rotate in a range RPM of 20 – 20000, maximum torque of 130 Nm and with maximum feed speed of 50 m/min. Figure 1 shows the schematic representation of the machining process. The burr measurements are made by Scanning Electron Microscope (SEM) HITACHI TM3030 Plus. The design of the experiment for the Y-type aluminium microchannels puncher is outlined in Table 3.

Table 1
Factors and machining levels

Factor	Levels		
	Low	Moderate	High
Spindle speed (r/min)	8000	14 000	20 000
Feed rate (mm/min)	30	90	150
Depth of cut (µm)	20	50	80

Table 2
End mill specifications

Diameter (mm)	Flute length (mm)	Helix angle (°)	Overall length (mm)	Shank diameter (mm)
2	6	50	50	4
4	11	50	50	4

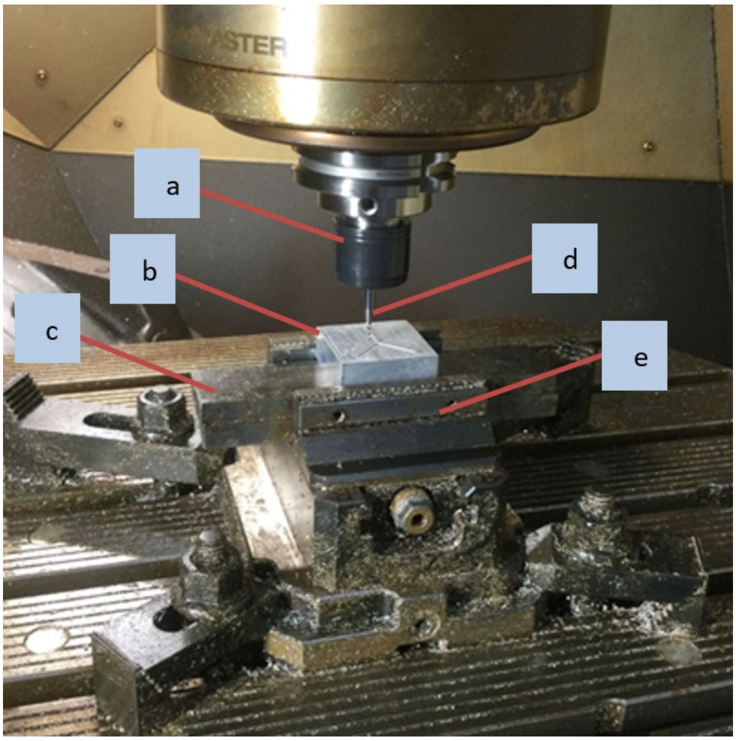


Fig. 1. The machining setup (a) tool holder (b) workpiece (c) parallel bar (d) end mill (e) precision vise

Table 3
Design of experiment

Sample	Spindle speed (r/min)	Feed rate (mm/min)	Depth of cut (μm)
1	20000	150	80
2	8000	90	50
3	14000	90	50
4	20000	30	80
5	14000	90	20
6	8000	150	80
7	20000	30	20
8	8000	30	20
9	14000	90	50
10	14000	90	50
11	8000	30	80
12	20000	90	50
13	14000	90	50
14	8000	150	20
15	14000	90	50
16	14000	150	50
17	14000	30	50
18	14000	90	50
19	20000	150	20
20	14000	90	80

2.2 Workpiece Preparation

The experiments are performed on Aluminium (Al6061-T6) steel with the dimension of 40 mm x 40 mm x 15 mm. The workpiece surface is made as flat as possible by face milling process. In this experiment, four flutes uncoated solid carbide end mills with diameters of 2.0 mm and 4.0 mm are used. Figure 2 shows the machined Y-type microchannel puncher on the aluminium block workpiece. The channel height is 100 µm and the width is 200 µm. The CATIA software is used to design the micro-channel features and to generate the CNC programming. Before the actual machining, the Al6061-T6 block workpiece was first flattened using face milling to ensure the surface was perfectly flat.

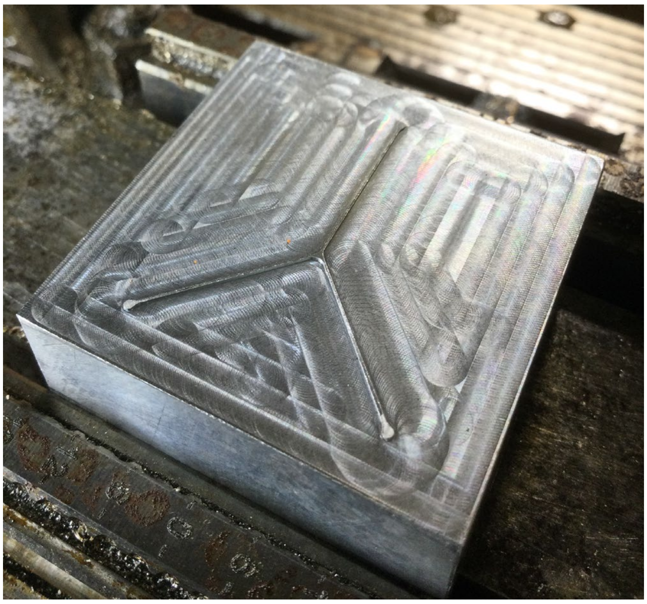


Fig. 2. The Y-type aluminium microchannel puncher

2.3 Burr Measurement

The machined workpiece undergoes inspection using a HITACHI TM3030 Plus Scanning Electron Microscope (SEM) to quantify the burr width. Burr formation in this Y-type Al6061-T6 microchannel puncher has been identified at seven primary locations. At each location, the maximum burr value was measured three times, and the average values of the burr dimensions were considered. Figure 3 illustrates the SEM image of the width of the top micro-burr formation.

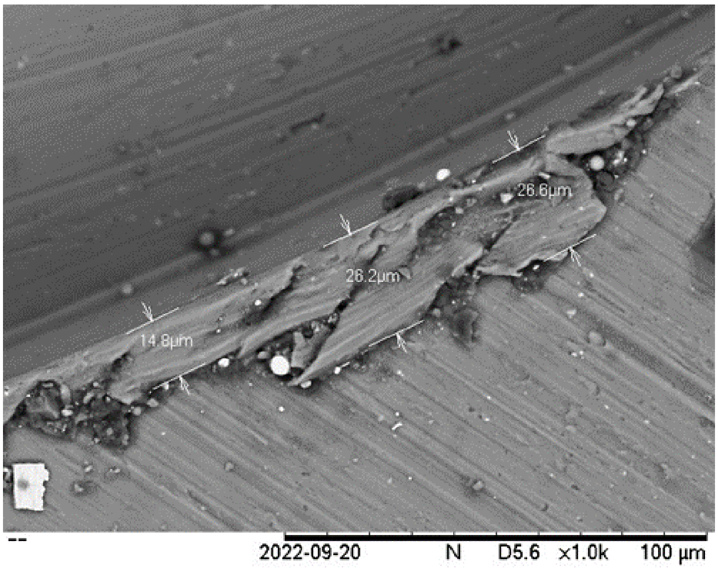


Fig. 3. SEM image of the top micro-burr width measurement

3. Results and Discussion

3.1 Effect of Machining Parameters on Top Micro-Burrs Formation

The general trend shows that burr width will increase simultaneously when the feed reed increases. This can be seen in the experiment that uses a high feed rate of 150mm/min. Figure 4 shows the average burr width for the experiments that used the highest feed rate was 56.4 µm compared to only 29.68 µm for the one that used the lowest feed rate. A comparison of burr formation for each location measured showed a significant difference in straight and curved channel for those using the higher and lower feed rates. For lower and higher feed values, straight channel burrs are almost comparable to curved burrs. Figure 5 shows SEM images of the top burrs formed while milling a Y-type aluminium microchannel puncher using a higher feed rate, while Figure 6 shows when using a lower feed rate. This aligns with the finding made by Khan *et al.,*[14], indicating that at lower feed rates, the primary mechanism contributing to burr formation is plowing, and the impact of the depth of cut radius is minimal. During this phase, the cutting tool displaces material rather than efficiently removing it. Plowing is particularly noticeable at lower feed rates, where the cutting forces might not be adequate to lift the material away, causing the tool to push or displace the material. However, at higher feed rates, the effect of the depth of cut radius becomes more pronounced, resulting in larger-sized burrs everywhere as reported by Khan *et al.,*[14]. As stated by Hajiahmadi [16], increasing feed rates leads to an increase in uncut chip thickness, facilitating the movement of the workpiece across the tool rake face at a greater velocity. Consequently, this scenario heightens the likelihood of increased tool wear. The enhanced plastic deformation and ductility of the material contribute to an increase in burr size.

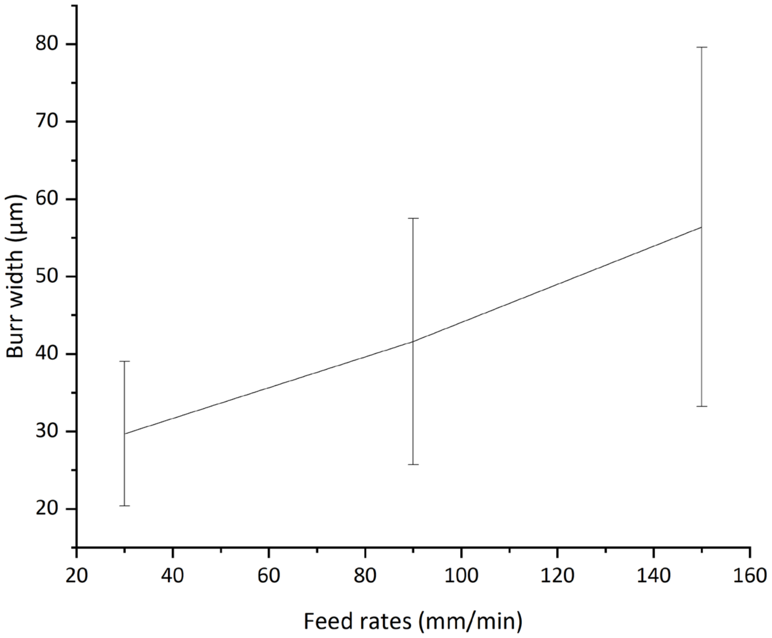
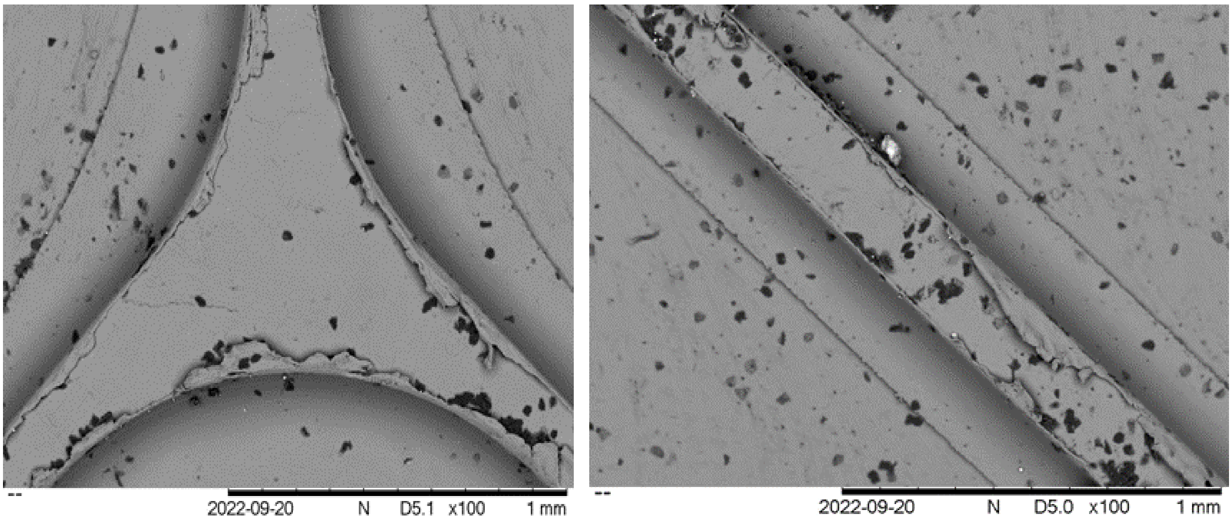
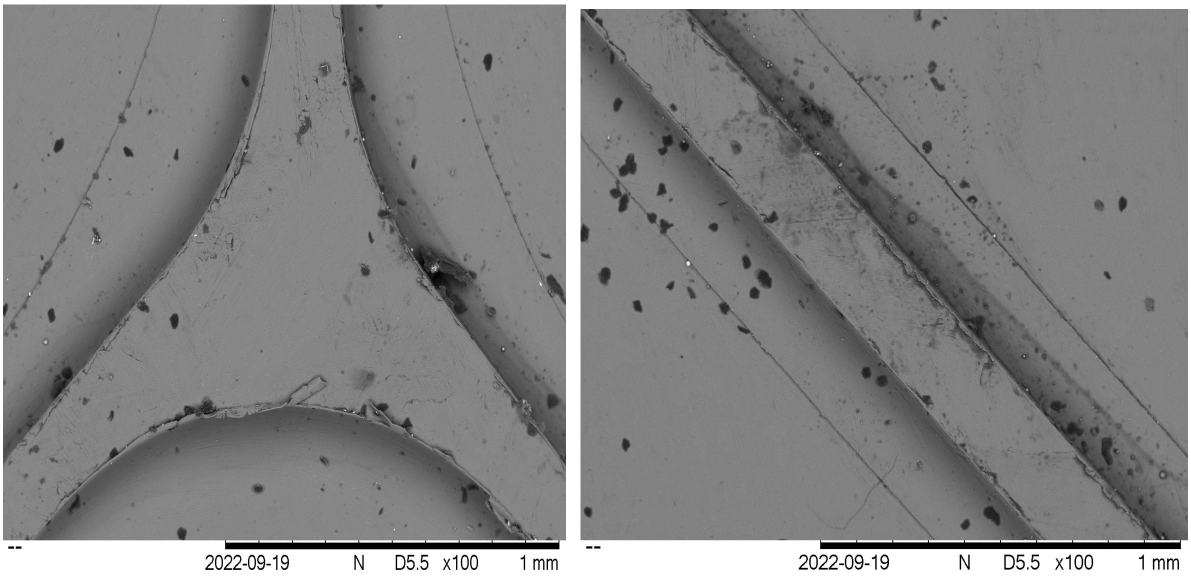


Fig. 4. Effect of feed rates on micro-burr width



(a) (b)

Fig. 5. SEM images of micro top burr for 150mm/min feed rate, spindle speed of 8000 r/min, and Depth of cut 20µm; (a) curve section ;(b) straight section



(a) (b)

Fig. 6. SEM images of micro top burr for 30mm/min feed rate, spindle speed of 8000 r/min, and Depth of cut 80µm; (a) curve section ;(b) straight section

Figure 7 shows that the burr dimensions increase as well as decreasing the depth of cut. The lowest burr dimension is at 50 µm depth of cut. More burrs appear if the cutting depth used is too low, due to the plowing action will be more dominant compared to machining. While for a higher cutting depth, more burrs are also formed because the amount of material that is plastically deformed likewise rises as tool edge engagement length increases as reported by Khan *et al.,*[14]. This can also be related to the effect of cutting force during the machining process. Based on a study by Sun *et al.,*[19], there is a similar relationship between the effect of depth of cut on cutting force and burr width. The micro-milling forces subsequently grow as the axial depth of the cut increases. However, the cutting force will decrease at an axial depth of cut of 40 µm due to the presence of an inflection point. This is where the critical undeformed chip thickness has been reached by the end-cutting edges at this cutting depth. Cutting force will reach the lowest value as chips are beginning to continuously generate by the end cutting edges. This effect will also result in minimal burr formation. As the depth of cut increases, the cutting tool is pushed deeper into the work material, resulting in grooves being impressed on the machined surface due to the greater cutting load. A high cutting load will lead to a higher cutting force that results in increasing burr formation as reported by several authors [14-16].

Figure 8 shows the effect of varying spindle speed on the microchannel burr width following a similar pattern to the impact of depth of cut on burr formation observed in this study. Burr formation is more likely to occur at low spindle speeds due to slower cutting action, resulting in material push-out and rough edges. The slower cutting action can cause the material to push out of the workpiece rather than being cleanly cut. Using an average spindle speed can help reduce burr formation, as it balances cutting speed and force. The cutting action is not too slow to cause material to push out of the workpiece, and not too fast to cause excessive material removal that leads to burr formation. When using a high spindle speed, there is also a risk of increasing burr formation. This can occur if the cutting tool is not sharp enough or if there is excessive pressure on the tool. However, if the cutting tool is sharp and there is the appropriate amount of pressure, a high spindle speed can help minimize burr formation by cleanly cutting through the material. As spindle speed increases, the cutting temperature rises, reducing flow stress during cutting. This enhances plastic deformation and material ductility, resulting in increased burr size. Increasing spindle speeds will also enhance the cutting velocity across the tool rake face, subsequently accelerating the issue of cutting tool wear. Machining with a worn-out cutting tool induces plowing action, leading to the formation of larger burrs, as reported in previous studies [16,20,21]. The combination of 14000 r/min spindle speed, 50µm depth of cut, and 30 mm/min feed rate leads to a low burr size, as inferred from Figures 3,6 and 7. That refers to sample number 17 which exhibits the lowest burr width of 17.9 µm among all samples tested in this experiment.

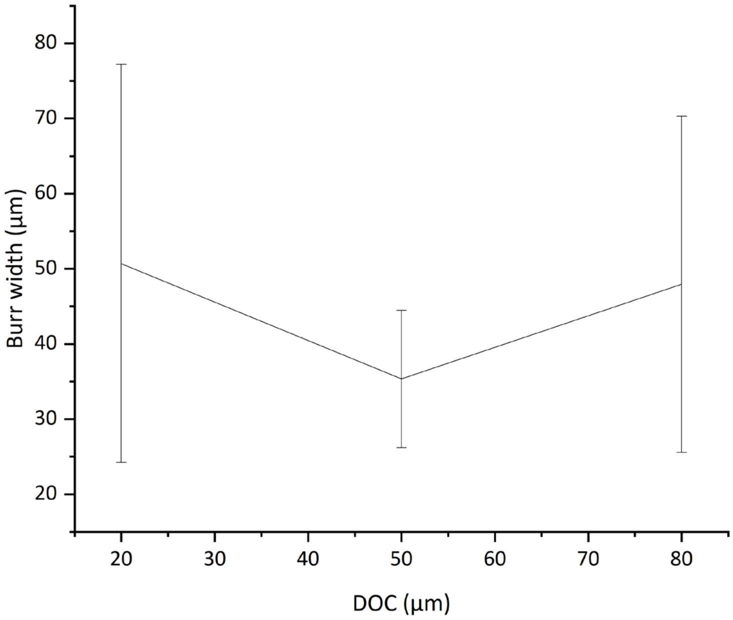


Fig. 7. Effect of depth of cut on micro-burr width

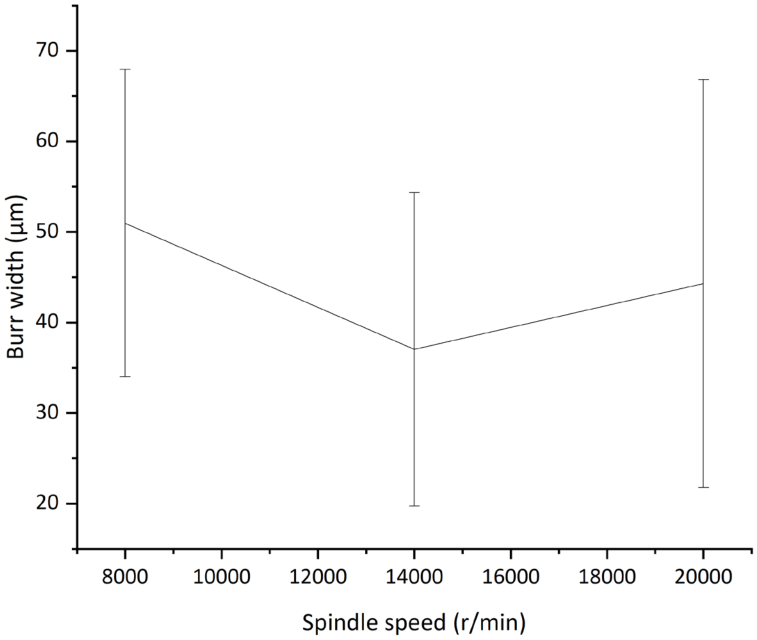


Fig. 8. Effect of spindle speed on micro-burr width

3.2 Micro Burrs Formation Size for Different Locations for Each Experiment

Figure 9 displays twenty experimental data for the average micro burr formation size across seven measurement locations in the Y-type Al6061-T6 microchannel puncher. The results show an average maximum micro-burr size of 82.2 µm in sample 5 (spindle speed: 14000 r/min, feed rate: 90 mm/min, depth of cut: 20 µm) and an average minimum micro burr size of 17.9 µm in sample 17 (spindle speed: 14000 r/min, feed rate: 30mm/min, depth of cut: 50 µm). Samples 10, 11, and 12 exhibit an average micro burr size ranging from 35-47 µm, each with different combinations of spindle speed, feed rate, and depth of cut. These findings highlight the influence of feed rate, depth of cut, and spindle speed, echoing the effects discussed in previous sections. A low depth of cut induces plowing, leading to increased burr formation due to tool edge engagement in chip removal from aluminum materials.

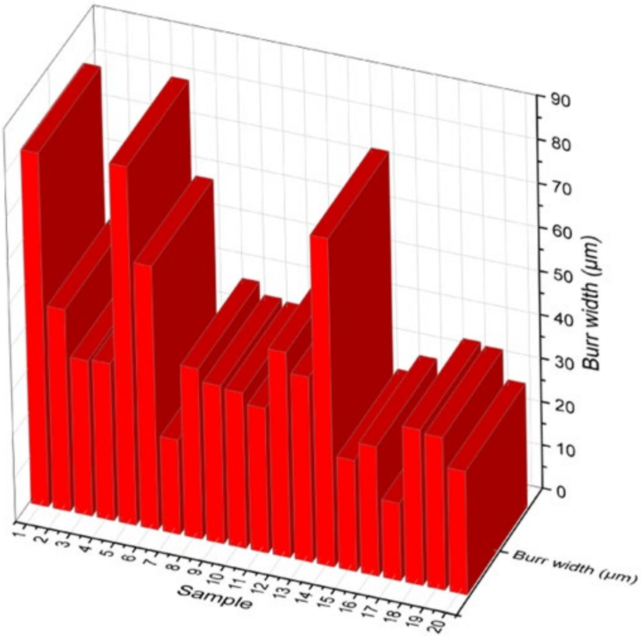


Fig. 9. Average micro-burr width by experiment

In Figure 10, the average micro burr formation is influenced by measurements at seven different locations using a Scanning Electron Microscope (SEM). Sample 5 exhibits the highest burr size, sample 12 shows the average size, and sample 17 has the smallest size. The largest micro burr size in sample 5 is influenced by locations 3, 5, and 7. The average micro-burr size in sample 12 is influenced by locations 5 and 7, while the smallest micro-burr size in sample 17 is influenced by locations 1, 4, 6, and 7. Furthermore, Figure 11 provides detailed images of the micro-burr for samples 5, 12, and 17 at locations 3(a-c), 4(d-f), 6(g-i), and 7(j-l). At location 3, the micro burr sizes for samples 5, 12, and 17 are 116 µm, 42 µm, and 17.8 µm, respectively, with curved sections. The top burr width reduces by 84.7% for sample 17 compared to sample 5 at the curved channel. Similar reductions are observed at locations 4 and 6, with reductions of about 79.9% and 57.9%, respectively, for sample 17. Conversely, the micro-burr size increases by 87.8% at location 7. Burr formation in micro-machining depends on machining parameters and other factors. Analyzing burr formation in straight and curved sections reveals higher values in straight sections at lower feed rates, while curved sections exhibit more burrs at higher feed rates. The limited impact of the curvature effect at lower feed values results in nearly identical burrs in both slot types, maintaining a consistent plowing region at low feed rates. As feed values increase, the curvature effect becomes more prominent, leading to a higher number of burrs in curved slots, aligning with findings by Khan *et al.,*[14].

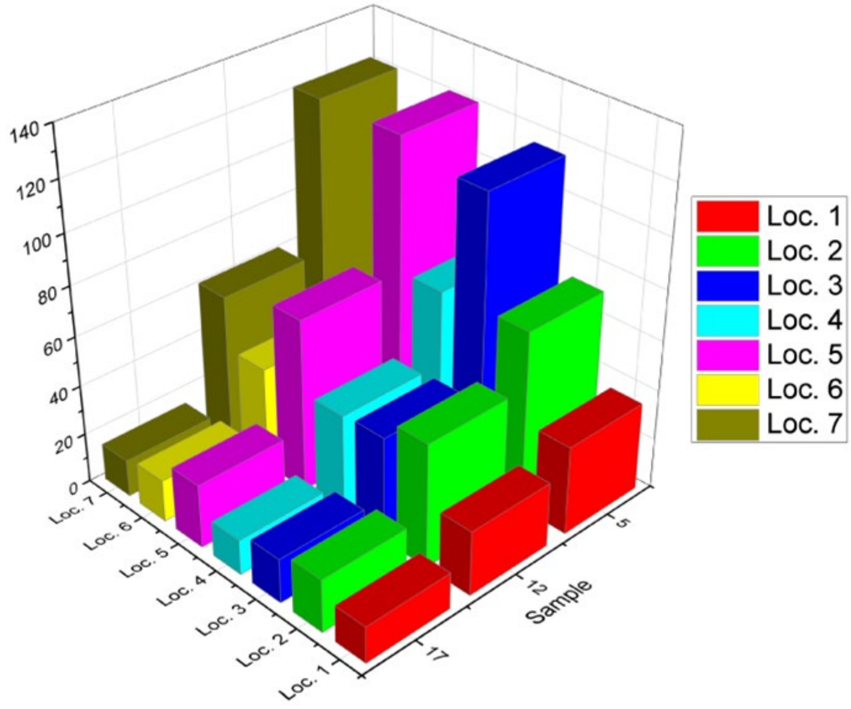
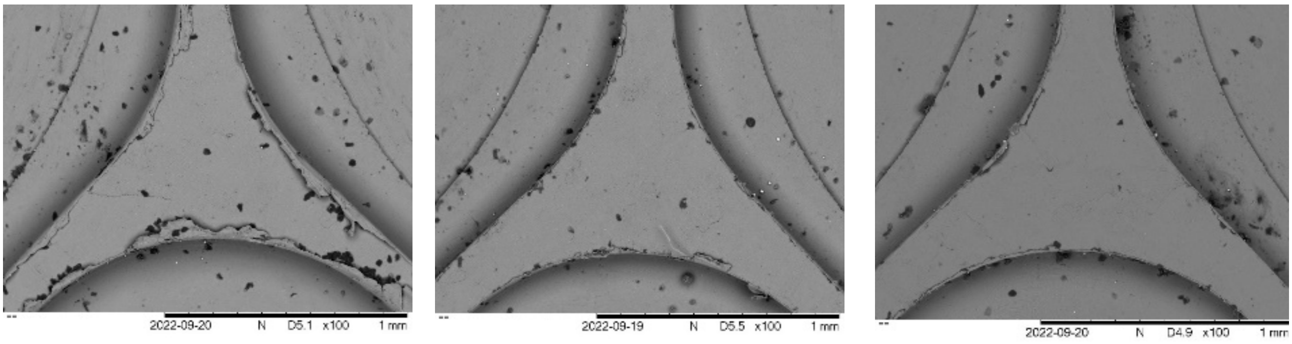
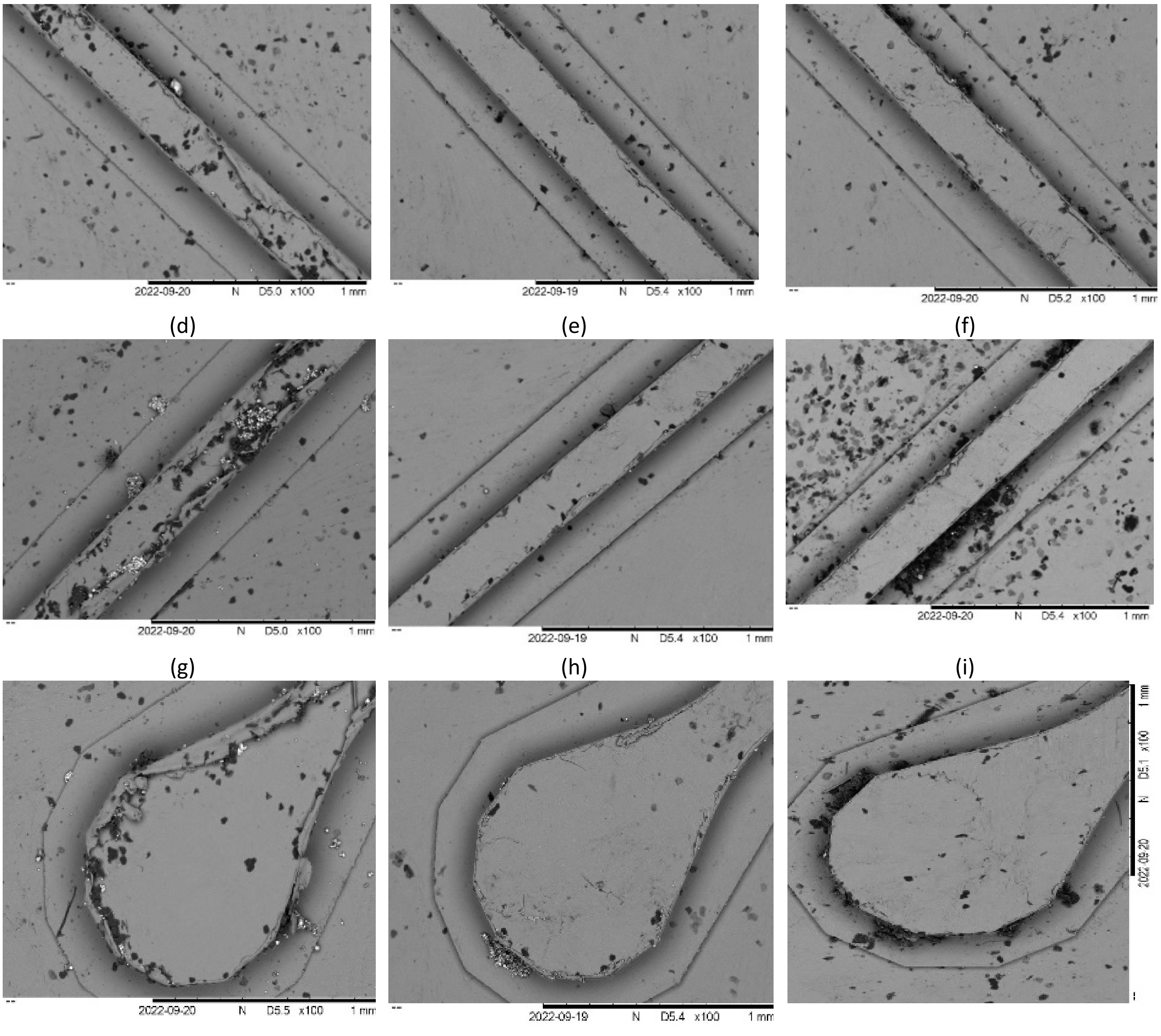


Fig. 10. Micro-Burr width by location for sample number 5,12 and 17



(a) (b) (c)



(d) (e) (f)

(g) (h) (i)

(j) (k) (l)

Fig. 11. SEM images of micro top burrs for samples 5, 12, and 17 at three different locations

4. Conclusions

The experimental study exposes how machining parameters impact the micro-burr formation in the Y-type Al6061-T6 microchannel puncher. The observed micro-burr size reflects the influence of machining process parameters, such as feed rate, depth of cut, and spindle speed, in high-speed machining. The following conclusions can be drawn from these findings:

i. The width of the top micro-burrs in the Y-type Al6061-T6 microchannel puncher is primarily influenced by feed rates, as opposed to spindle speed and depth of cut. Significant variations in burr width have been observed with increasing feed rates. The burr size increases when the feed rate is raised from 30mm/min to 150mm/min. Recorded values for burr width at the maximum feed rate (150mm/min) are 81.2 µm, 60.6 µm, 75.2 µm, 29.8 µm, and 35.1 µm.
ii. At lower feed rates, plowing is the primary mechanism for burr formation, with minimal influence from the depth of cut radius. The cutting tool displaces material instead of

efficiently removing it, especially noticeable when cutting forces are insufficient to lift the material, causing the tool to push or displace it.

iii. At higher feed rates, the depth of cut radius has a pronounced effect, resulting in larger burrs. Increased feed rates elevate uncut chip thickness, enhancing workpiece movement across the tool rake face and heightening the likelihood of increased tool wear due to enhanced plastic deformation and material ductility.

iv. Burr dimensions increase with decreasing depth of cut, reaching the lowest dimension at a 50 µm depth. Insufficient cutting depth leads to increased burr formation due to the dominance of plowing over machining. Conversely, higher cutting depths also result in more burrs as the plastic deformation of material increases with the longer engagement length of the tool edge.

v. Burr formation is likely at low spindle speeds, causing material push-out and rough edges. Maintaining an average spindle speed reduces the risk of burr formation, while high speeds can lead to excessive material removal and potential burr issues. Increased spindle speeds enhance plastic deformation and material ductility, resulting in larger burrs. Additionally, higher speeds accelerate cutting tool wear, inducing plowing action and larger burr formation.

vi. Comparing burr formation in straight and curved sections reveals higher values in straight channels at lower feed rates. Curved slots exhibit more burrs at higher feed rates. The limited impact of the curvature effect at lower feed values results in similar burrs in both slots. A low feed rate maintains consistent plowing. Conversely, increasing feed values make the curvature effect more prominent, leading to more burrs in curved slots.

vii. The lowest burr width, which corresponds to sample number 17, was achieved with the following combination of parameters: moderate spindle speed of 14000 r/min, low feed rate of 90 mm/min, and moderate depth of cut of 50 µm.

viii. The largest burr size that showed significant burr formation is sample number 5. This represents a combination of machining parameters of moderate spindle speed of 14000 rev/min, moderate feed rate of 90 mm/min, and low depth of cut of 20 µm.

ix. Sample 14 exhibits a notable formation of burrs with a high feed rate of 150mm/min, low depth of cut of 20 µm, and low spindle speed of 8000 r/min. The burr width is 75.2 µm, and the SEM image confirms the substantial presence of burrs in all checked areas.

x. The primary mechanisms for micro-burr formation include plowing, rubbing, and plastic deformation. Burr size and shape depend on factors like cutting parameters, tool geometry, material properties, and workpiece fixturing. Other factors like tool wear, deflection, and vibration can also impact burr formation by causing variations in cutting force. Future experiments are required to further explore these influences on micro-burr formation.

Acknowledgement

This research was funded by a grant from Universiti Malaysia Pahang Al-Sultan Abdullah (UMPSA) Post Graduate Research Scheme (PGRS2003176).

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