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Effect of Cutting Environment and Swept Angle Selection in Milling Operation

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ABSTRACT

Cutting fluids are frequently aimed to enhance machinability through cooling, lubricating and flushing actions. However, their use in machining creates major concerns in terms of health footprint and environmental effects throughout their lifecycle. Alternative methods, such as dry cutting and minimum quantity lubrication, were used to mitigate these issues. This research also will investigate the effect of swept angle selection, 30% and 60% of tool diameter step over under different cutting conditions during milling of aluminium alloy material. Their impact on tool wear, surface roughness, burr and chip formation were compared. Results pointed that the application of lower swept angle in conjunction with minimum quantity lubricant system has significantly reduced tool wear, decreased burr and chip formation, as well as improved surface quality as compared to dry machining. The work clearly shows how the importance of swept angle selection and cutting condition in refining machining performance could improve the machinability of the material.

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NOMENCLATURE

L_c	length of chip	R_a	surface roughness arithmetical mean
V_B	flank wear	W_b	burr width
r_e	cutting edge radius		

1. INTRODUCTION

In machining processes, cutting fluids are commonly used for cooling, removing metal particles, reducing friction, and protecting the tool, workpiece and machine tool [1]. In addition, it is also responsible for a variety of secondary functions, such as transporting chips, cleaning of tools, workpieces, and fixtures. However, some drawbacks have also been correlated with the use of cutting fluids because of their cost, environmental impact, and hazards to workers [2]. Additionally, this cutting fluid also has a harmful impact on health such as leukemia, skin cancer, lung cancer, asthma etc. [3]. Therefore, numerous substitutions to the conventional cutting fluids are currently being explored in the industry.

New methods have been developed over the past decades to address the major difficulties of cutting fluids. The key alternatives such as dry machining and minimum quantity lubrication (MQL) were commonly evaluated from a technical point of view and have been found as viable substitutes in optimizing machining performance as well as diminishing hazards [4]. To avoid risky cutting fluids during the machining process, dry machining is appointed. This owing to its benefit that translated into zero pollution when no need a cost for coolant, its maintenance, and disposal [5]. Nevertheless, dry machining causes excessive temperature increases which leads to poor tool life and damage to the machined surface [6]. Wherever it is not possible to completely remove cutting fluids, a very small amount of lubrication,

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pulverized only at a required point, which is known as Minimum Quantity Lubrication Machining (MQL), is used [7]. This method helps to improve surface finish quality and tool life, minimize lubrication costs, and decrease tool wear and cutting temperature.

Aluminium makes up about 70% of the whole Boeing 777 [8]. The main factor for its use is its high strength-to-weight ratio. However, the use of aluminum, whose high thermal conductivity combined with extreme adherent tendency causes excessive heat generation at the cutting zone, and difficulties in heat dissipation [9]. Common issues in the machining of aluminum alloys are built- up edge and adhesion of the material to cutting tool due to high ductility and thermal conductivity of the work material [10].

Milling is one of the most popular common manufacturing processes to remove material from a workpiece with a rotary cutter by moving towards an angle with the machine axis [11]. Due to the various degree-of-freedoms in the milling process, complex structures could be produced. In milling, cutting speed, spindle speed, depth of cut, and feed rate are the main governing parameters [12]. The relationship between the cutting tool and surface quality is also closely related. In addition, cutting parameters, tool life, machine tool characteristics, process variables, and workpiece materials all played a role in mechanical machining. It is a key performance metric that monitors surface integrity and ready-to-use consumer aesthetics [13]. Although the swept angle is one of the main parameters that determine the tool wear, surface roughness, burr and chip formation characteristics, its importance has not been well investigated and documented in the literature.

Swept angle or tool engagements are identified as part of the tool involved in the workpiece during the process of machining which the swept angle is an important factor that affects the tool wear, surface roughness, chip formation, and burr formation during slot milling. Hence, when the cutting tool and workpiece are fully engaged, the resulting effect would be greater [14]. Therefore, the purpose of this research is to perform an experimental study on the effect of the swept angle selection under the different cutting conditions in the milling process. The following sections will provide a detailed explanation for the study.

2. EXPERIMENTAL DETAILS

2. 1. Experimental Setup and Machining Conditions

The workpiece material selected to be machined was a rectangular aluminium alloy 7075 with dimensions of 150 mm width, 150 mm length, and 4 mm height. 4-flutes end mill high speed steels (HSS) cutting tool with 4.0 mm diameter was used. This experiment was conducted using Tongtai EZ–5A CNC Milling Machine. A constant cutting velocity of 63 m/min, table feed rate of 440 mm/min, and depth of cut of 1 mm were used as established from pilot tests.

Two different cutting conditions were studied, namely dry and minimum quantity lubricant (MQL) with base lubricant (Solcut oil). For MQL, the nozzle was placed at the tool entry point to enhance oil entrapment [15]. The flow rate was 40 ml/h with a compressed air pressure of six bar. In this experiment, two values of swept angle were used for each condition; 30% and 60% of tool diameter stepover. Each condition was repeated three times using new cutting tools.

2. 2. Swept Angle Selection

A swept angle refers to the percentage of the tool that engages in the machining process with the workpiece. The values will be chosen using Equation (1):

$$Swept\ angle = \frac{tool\ step\ over\ (\%)}{100} \text{ x } tool\ diameter \qquad (1)$$

Figure 1 shows the swept angle of the cutting tool on the workpiece which consists of 66.4° (30% tool diameter stepover) and 101.5° (60% tool diameter stepover). Both stepovers were selected to signify high and low angle of engagement.

2. 3. Tool Wear, Cutting-edge Radius, Surface Roughness, Burr Formation and Chip Length

Every tool and workpiece for each cutting condition was then examined using Xoptron XST60 Stereo Microscopy System to capture tool wear, burr and chip formation. Flank wear (V_B) were measured on the side flank face, and cutting-edge radius (r_e) was determined by placing the best-fitting circle at the tool flank face intersection. While a width of burr formation (W_b) was measured for top burr. Then, the length of chip formation (L_c) was also quantified. For all measurements, a Java-based image processing, Image J software was used concurrently. A Mitutoyo F-3000 surface roughness tester was used to measure surface roughness using arithmetical mean (R_a) value. Systematic uncertainties were minimalized by first calibrating the equipment to be used. In addition, random vagueness was addressed by performing each measurement at least five times.

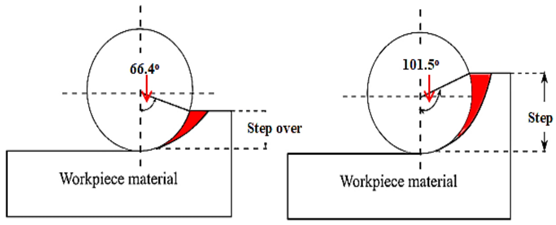

Figure 1. Swept angles of the cutting tool on the workpiece

3. RESULT AND DISCUSSION

3. 1. Tool Wear Modes Optical images were used to identify the wear modes after milling ten consecutive slots. In this experiment, several types of wear were found i.e. outer corner wear, crater wear, chipping, and flank wear. Among all wear modes, the most dominant was flank wear. Figure 2 shows examples of wear modes that could be witnessed on the cutting tools. The main reason for these occurrences is due to high force and continuous contact between the tool and the workpiece during penetration that lead to heat generation through frictional action. It is pertinent to note that the thermal property (i.e. conductivity) of the HSS cutting tool is significantly lower than aluminum workpiece, therefore, most of the heat that generated in all shear zones are likely to circulated in the workpiece. This situation would soften the workpiece material thus resulting in welded chips or material adhesion that cause build-up in the flute area specifically under dry cutting. This phenomenon could drive to premature process disturbances.

3. 2. Tool Flank Wear For the flank wear measurements, the tools were imaged from the bottom face. The results have shown that the flank wear (VB) was significantly affected by the swept angles and cutting conditions. Figure 3 shows the average flank wear growth for different swept angles and cutting conditions.

It can be seen clearly that machining under dry cutting condition shows a substantial amount of wear on the flank surface, as shown in Figure 4. Meanwhile, machining under MQL confronts lesser values under similar parametric settings condition. This is due to the fact that the oil which acts as a cooling and lubricating agent could significantly reduce the temperature and frictional forces between the cutting tool and workpiece.

It can be observed that under MQL condition the cutting-edge shape was relatively sharper compared to dry cutting which was rounded in shape.

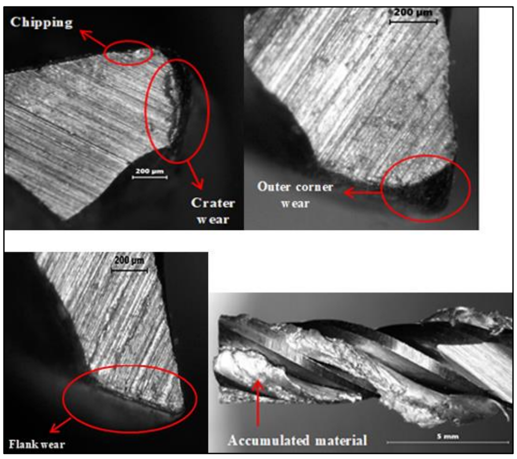

Figure 2. Tool wear modes

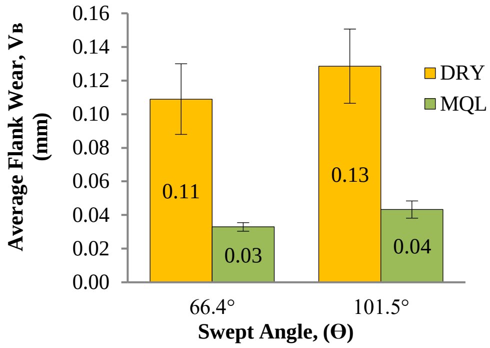

Figure 3. Average flank wear under different swept angles and cutting conditions

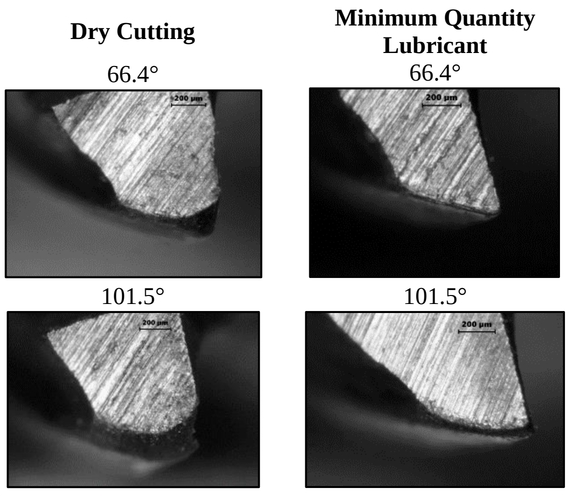

Figure 4. Tool wear growth for both different swept angles and cutting conditions

The highest flank wear was attained under swept angle 101.5° for both cutting conditions. This has happened for the reason that an increase in swept angle leads to excessive tool loading and deflection, thus resulting in an increase in tool wear. As a result, the both cutting condition (dry and MQL) display a slight increment. With 66.4° swept angle, the average flank wear was lowered by 15% and 25% respectively under dry and MQL condition. Despite a significant difference in flank wear values, both conditions are acceptable according to ISO 8688-2 [16], which is below 0.3 mm. It is also noted that the flank wear in the cutting process with both swept angles 66.4° and 101.5° under MQL condition is significantly lower compared to dry condition. In addition, the use of the smaller value of swept angle also contributes to lesser flank wear.

3. 3. Cutting Edge Radius Cutting edge radius was also used to monitor the tool condition since it is an appropriate indicator of the amount of tool wear. The edge corner radius of the tool was measured by fitting a circle tangent line to straight lines. In this experiment, edge radius (r_e) deterioration was found on the tool cutting edge. Figure 5 shows the changes of cutting-edge deterioration for both conditions after machining processes.

Figure 6 shows the changes of cutting-edge radius for both swept angles and cutting condition. In this figure, more effective cutting-edge radius occurred when using the swept angle of 66.4° compared to the swept angle of 101.5°. But, the values for dry and MQL (after machining) shows prominent changes, especially under dry condition. Furthermore, as expected, the higher swept angle implied a higher value of r_e, which increased by 90% and 68% under dry and MQL conditions, respectively, when compared to the lower swept angle. Dry cutting contributed to higher Re due to lack of lubricating and cooling action that led to higher specific cutting energy. In general, the result showed that the use of a lower swept angle has resulted in lowering tool wear by retaining the sharp edges for both conditions.

3. 4. Surface Roughness

Surface roughness (R_a) is a measured parameter that can be used to analyze the quality of the machining process. It should be noted that roughness quality sturdily depends on feed per tooth and tool edge radius. In this experiment, average surface roughness was measured at three main points, i.e. entry, middle, and exit. Figure 7 shows the variations of average surface roughness under different swept angles and cutting conditions.

The roughness has been evaluated using the arithmetic average deviation of profile, R_a. These bar graphs give an insight into how the surface responds to change in swept angle for both dry and MQL environments. From these results, it can be seen that the 101.5° of swept angle produces the higher Ra as compared to the 66.4° of swept angle. Besides, under dry condition, machined surfaces appear rougher, especially with adhered or sticky material. It is obviously seen in Figure 8. In contrast, it was found that the adhered material was completely removed when MQL was applied. This could be due to the application of MQL reduces the temperature effect and hence; the adherence propensity.

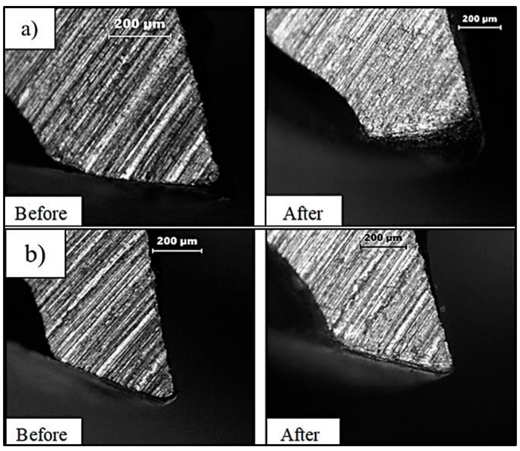

Figure 5. Cutting-edge deterioration under (a) Dry cutting and (b) MQL condition

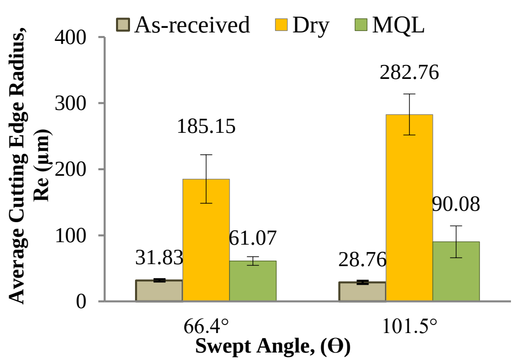

Figure 6. Changes of cutting-edge radius for both swept angles and cutting conditions

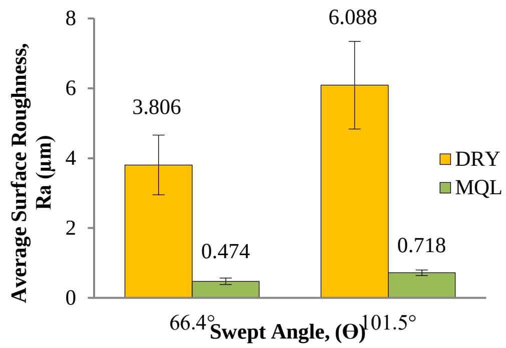

Figure 7. Average comparisons for surface roughness, Ra.

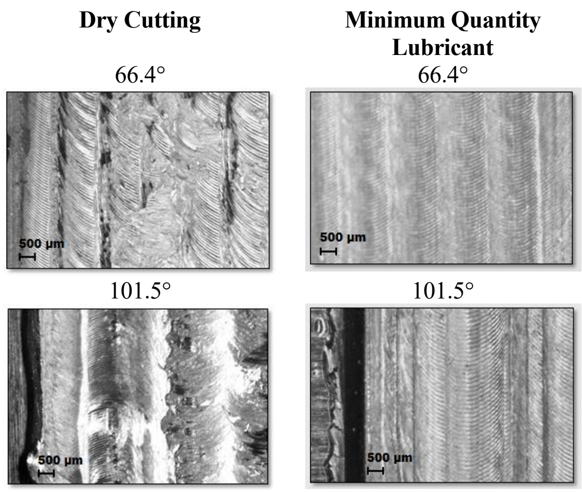

Figure 8. Surface pattern for both swept angles and cutting conditions

The results also appear that R_a grows rapidly under dry condition when compared to MQL method. This is due to more intensive stress and temperature at the workpiece and tool interface that lead to quick tool wear. Under MQL method, the pressurized air with oil to the cutting zone promotes rapid removal of the chips whilst retaining the tool shape. Higher tool wear and chipping could create valleys and marks on the machined surface. Also, it is important to note that due to the high ductility of aluminium, it could promote roughness on the surface.

Overall, it is concluded that the lower swept angle by varying machining under MQL condition provide superior surface finish than dry condition as step-over reduced the interruption in cutting process. In addition, lubricant used in MQL would lessen adhesion and interaction of tool and workpiece thus reducing friction as well as tool wear.

3. 5. Burr Formation There were four types of burr created which were top burr, exit burr, entrance burr, side burr, and bottom burr. They were designated through their cross-sectional area. It was found that the most dominant burr was the top burr which formed on top of the workpiece surface. Figure 9 shows the top burr formation under different swept angles and cutting conditions where different features could be identified. Wider top burrs with large curvature were created under dry cutting, in comparison with those obtained in MQL which was thinner. Under MQL, the use of oil makes the shearing process became smoother and easier, and hence resulting in reduced burr size.

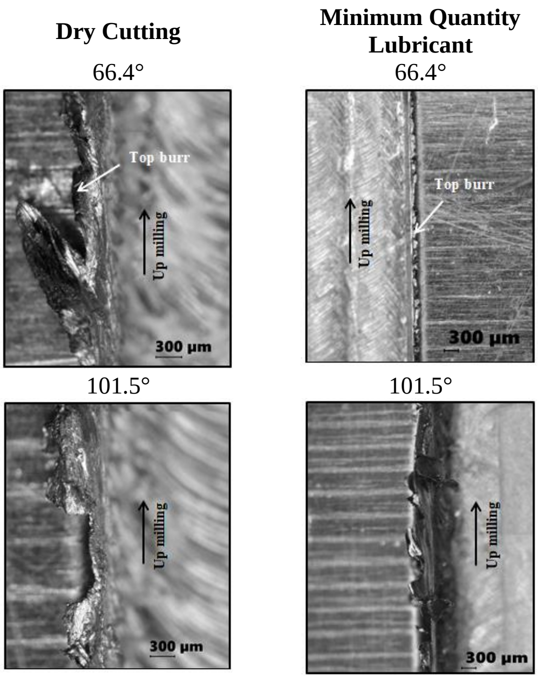

Figure 9. Burr formation under different swept angles and cutting conditions

Figure 10 shows the average burr width under differe nt cutting conditions. It can be seen that a significant red uction in burr width values was obtained with MQL syst em. This improved performance was possibly due to the enhanced lubrication that retained the sharpness of the to ols. The reason why the tool wear rate under dry cutting is high is due to the ploughing effect, which happens wh en the cutters are not removing the material but pushing it off to the slot side instead to create burr. In addition, a larger swept angle also plays a significant role by increa sing the width of burrs.

Based on Figure 10, it shows that burr width (W_b) for after 10th slots produce bigger and wavier burrs compare to burr width for first slot. For a swept angle of 101.5°, the result shows an increasing pattern for both cutting conditions compared to the swept angle of 66.4°. It can be seen that the W_b was lessened under MQL method compared dry method for both swept angles. This is because the effect of the cutting fluid on tool wear and due to the amount of sweep subtended by cutting edge which makes them engages and leaves the workpiece during the slot milling process. Overall, the observed phenomenon is directly related to each other, where the swept angle will cause the tool wear and increase in the cutting-edge radius that would significantly increase the ploughing effect that would finally result in the formation of the top burr.

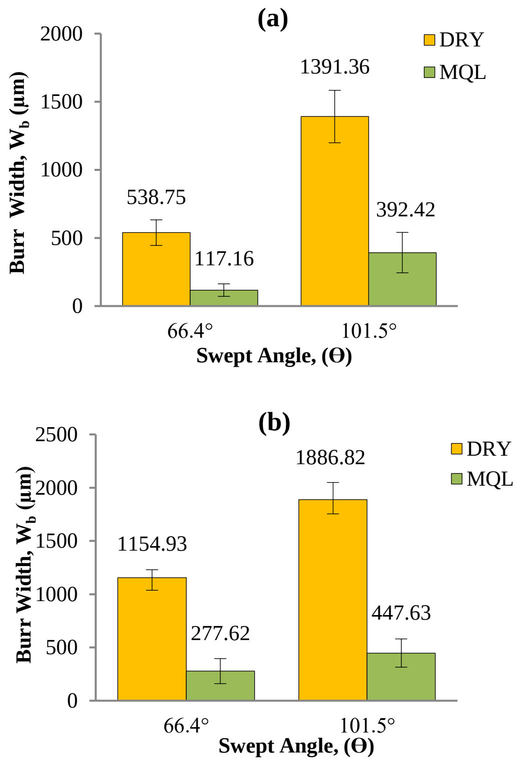

Figure 10. Average burr width under different cutting condition after (a) 1st slot; and (b) 10th slot

3. 6. Chip Formation The mechanism of chip formation is a major strain deformation method, with partial fracturing is caused by internal cracking or voiding in or near the primary shear zone and likely crack formation around the cutting edge. So, it is important to measure the length of chip formation for each chip collected from these experiments. Figure 11 displays the average comparisons between swept angles for the length of chip formation under different machining conditions.

The result shows that machining in dry condition formed longer chips than in MQL condition. This is particularly evident when a higher swept angle was used. In principle, the higher value of swept angle applied during operation, the longer the chips.

Microscopy images of chip formation in different swept angle and cutting conditions is shown in Figure 12. It shows a typical chip pattern when machining aluminum alloy under various cutting conditions. It is important to note that small well-broken chips are desirable in machining. A shorter chip was observed under MQL condition for both swept angles. While, continuous non-uniform with severe curled chips were found under dry cutting. This had happened due to the fact that the chips were exposed to intense heat and hence leading to huge plastic deformation. Under MQL condition, flat morphology of chips was formed owing to the reduction in cutting temperature. All the findings confirmed that lubrication action through MQL system is desirable in terms of chip formation as it produces shorter chip as compared to dry machining.

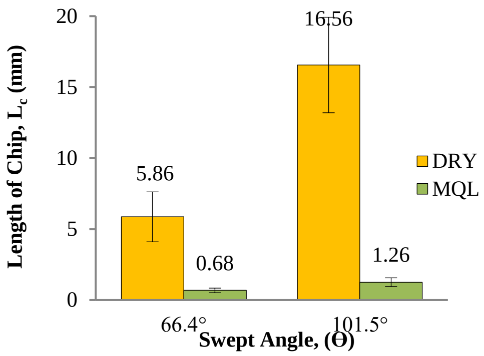

Figure 11. Average comparisons in length of chip formation

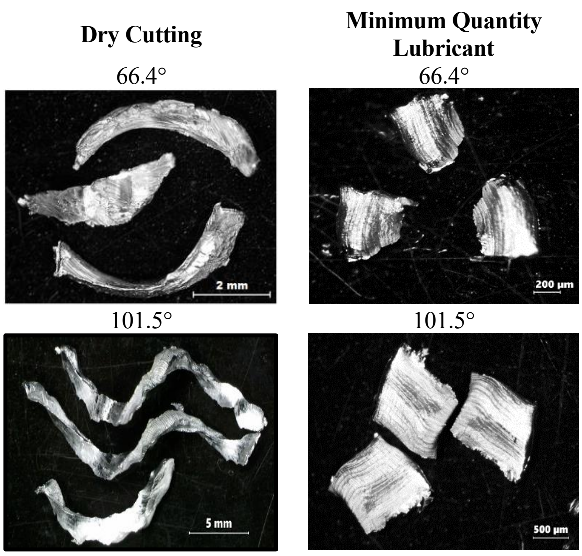

Figure 12. Chip pattern under different swept angles and cutting conditions

4. CONCLUSION

From this study, it was obvious that the significant used of minimum quantity lubrication (MQL) as an alternative method to substitute the used of conventional metal working fluid in machining operations was proven. Besides, the impact of swept angle selection and their influence under the different cutting conditions was also demonstrated. The result showed that the lower swept angle applied, the better result in the form of reduced tool wear and burr formation, improved surface roughness and chip formation. This is confirmed in both dry and MQL condition. Swept angle and cutting condition plays an important role in determining tool wear (flank wear and edge radius), surface roughness, burr, and chip formation. For that reason, the results established that a parametric combination between lower swept angle of 66.4° under MQL condition have demonstrated minimal tool wear and better surface quality.

5. ACKNOWLEDGEMENT

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Persian Abstract

چکیده

مایعات برش اغلب به منظور افزایش قابلیت ماشینکاری از طریق خنک کننده ، روان کننده و شستشو انجام می شود. با این حال ، استفاده از آنها در ماشینکاری نگرانی های عمده ای را از نظر ردپای سلامتی و اثرات محیطی در طول چرخه زندگی آنها ایجاد می کند. روشهای جایگزین ، مانند برش خشک و حداقل مقدار روغن کاری ، برای کاهش این مسائل استفاده شد. این تحقیق همچنین تأثیر انتخاب زاویه جارو شده ، ۳۰ و ۶۰ درصد قطر ابزار را تحت شرایط برش مختلف در طول آسیاب مواد آلیاژ آلومینیوم بررسی می کند. تاثیر آنها بر سایش ابزار ، زبری سطح ، شکل و شکل تراشه مقایسه شد. نتایج نشان داد که استفاده از زاویه جاروب پایین در ارتباط با حداقل مقدار سیستم روان کننده باعث کاهش قابل توجه سایش ابزار ، کاهش ساییدگی و تشکیل تراشه و همچنین بهبود کیفیت سطح در مقایسه با ماشینکاری خشک می شود. این کار به وضوح نشان می دهد که چگونه اهمیت انتخاب زاویه جارو و شرایط برش در پالایش عملکرد ماشینکاری می تواند قابلیت ماشینکاری مواد را بهبود بخشد.