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Impact of Tool Path Strategy and Pocket Geometry in Pocket Milling of Al 5083 Alloy

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Abstract— Pocketing is a common machining operation used in several industrial applications such as aeronautic, automotive, biomedical, shipbuilding, and die/mold fabrication. In pocket machining of sculptured parts, tool path creation is a vital step influencing overall machining performance. In the present study, the impact of employing different tool path strategies during pocket milling of different pocket geometries of aluminum Al 5083 alloy is experimentally investigated to evaluate the process performance in terms of surface roughness and machining time. Master CAM software has been used to select pocket milling tool path strategies: zigzag, constant overlap spiral, parallel spiral, parallel spiral with clean corners, true spiral, and one-way strategy. Three complex pocket geometries with different shapes, sizes, and interior islands have been milled and examined. Actual CNC and CAM simulated machining times are compared as well. The results indicate that the geometry of a pocket is directly proportional to its surface roughness. Parallel spiral generated the best surface finish, and the zigzag strategy achieved less machining times for all the pocket geometries.

Index Terms— Tool path strategy, Pocket geometry, Pocket milling, Surface roughness, Machining time.

I. INTRODUCTION

Complex-shaped objects are widely used in die/mold, aeronautic, automotive, shipbuilding, precision manufacturing, and other industrial sectors. Geometrical complexity and difficulty in machining such surfaces have been time- and cost-saving challenges. These complicated parts are usually produced from a raw stock by 2½ D roughing and then 3-5 D finishing. Most of mechanical parts can be machined using 2½ D axis milling as most of them consist of faces parallel or normal to a single plane [1], [2]. The task of 2½ D milling is also called pocket milling since all the machining is done in one plane, and that plane has a single depth in the third plane at each point. These pockets may have straight edges, curved edges, or a combination of both, as shown in Figure 1.

Moreover, machining pockets with interior islands increases the geometric and processing planning complexities. Particularly, the tool path control can be achieved easily and quickly in 2½ D pocket milling by reducing the total travel of the tool and thereby reducing the machining time. Thus, the productivity improvement of the 2½ D roughing is very beneficial to the industry [3], [4]. Unlike other milling operations, pocket milling has various tool path strategies to achieve the desired profile with different efficiencies. Two common tool path strategies are usually applied during pocket milling: direction parallel (zigzag) and contour parallel (spiral) tool paths. In the direction parallel tool paths strategy, the tool is moved along the line segments which are parallel to a specified direction such that they are either all traversed from right to left or from left to right (unidirectional) or from left to right and from right to left (bio-directional), see Figure 2 (a). In contrast, the contour parallel drives the tool along curves at a constant distance from the pocket's boundary, see Figure 2 (b). The most demanding task is the repeated generation of the individual offset curves used as tool paths [5]–[7].

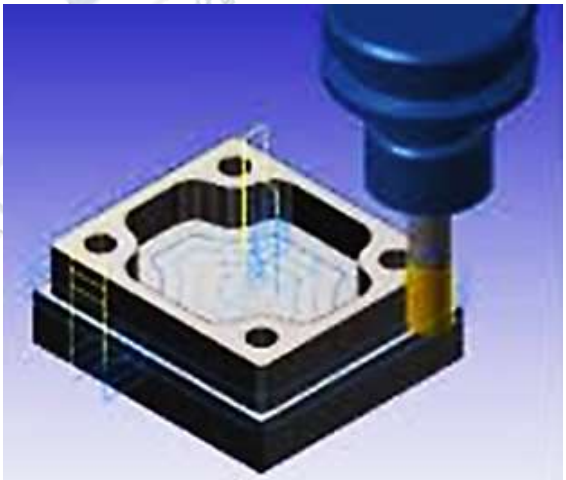
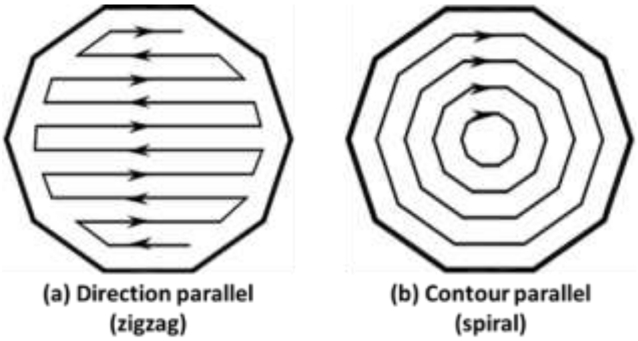


Figure 1. Illustration of pocket milling



(a) Direction parallel (zigzag)

(b) Contour parallel (spiral)

Figure 2. Two main tool path strategies in pocket milling: (a) Direction parallel and (b) Contour parallel

The appropriate determination and implementation of optimal tool path strategy in pocket milling is critical since it can significantly save machining time and increase tool life, leading to lower costs and higher productivity. Therefore, there has been significant growth in studying geometrical and computational solutions for pocket machining challenges. Moreover, research on CNC machining operations in relation to the tool paths designed in CAM software is becoming increasingly essential with the primary goal of faster machining time, less cost, and enhancing machining efficiency [8], [9]. In this regard, the effect of five cutting path strategies on aluminum 6061 alloy workpiece's surface roughness and the energy consumption of the machining process [3], the impact of three tool path strategies, namely inward helical, outward helical, and back and forth, on the machinability of aluminum epoxy during pocket milling of machining time, surface finish, tool wear, and tool life [4], and the influence of milling parameters and machining time on the surface roughness and tool wear in dry pocket milling processes of aluminum alloy Al7075 [5] was studied. Bağci et al. examined three tool path strategies, including contour parallel, spiral, and zigzag tool paths with different cutting angles on cutter deflection, cutting forces, sound pressure, and surface errors when rough machining of the complex surface of Al 7075-T651 with ball end mill. The conclusion was that the 0° zigzag strategy showed the lowest cutting forces, tool deflection, surface errors, and sound pressure. In contrast, the spiral strategy produced the worst surface errors and the highest cutting forces [1]. Prajapati et al. applied seven tool path strategies for pocketing aluminum turbine blades: zigzag, constant spiral, parallel spiral with clean corners, morph spiral, one way, and true spiral; then, machining and simulation results were compared. Experimentation revealed that the zigzag tool path was more advantageous with minimum cycle time and that the best path typically depended on the geometry and the cutting conditions [2]. In another work, the impact of pocket geometry and cutter path strategy on machining time, cutting forces, and surface roughness of UNS A96063 aluminum alloy was investigated using two tool path strategies (contour-parallel as direction-parallel) and three pocket geometries. It was concluded that it attained lower machining times, lower transversal and longitudinal surface roughness, and upper medium forces and vibrations [10]. Pinar et al. employed a parallel spiral tool path strategy and two cooling methods in pocket milling of AA5083-H36 alloy with an uncoated cemented carbide cutting tool to optimize surface roughness [7]. Samtaş et al. applied three tool path patterns (concentric, back and forth, and inward helical) to examine the surface roughness during pocket milling of tempered aluminum alloy 5754 using TiCN and TiAlN coated end mills [9]. Uzun et al. studied the effect of four tool path strategies, zigzag, zig, follow part, and trochoidal, on tool wear, machining times, and surface roughness during milling of AISI D3 Steel. The trochoidal tool path was successful with lower surface roughness and tool wear, while the follow-part strategy had the minimum machining time [8]. Gologlu et al. identified the effects of cutting parameters and cutter path strategies on surface roughness in pocket milling of DIN 1.2738 mold steel. Three cutter path strategies employed were one direction, back and forth, and spiral cutter path strategies. Results showed that the most influential effects that produced the best surface finish were feed rate for one direction, spiral cutter path strategies, and depth of cut for back-and-forth cutter path strategy [11]. Yazid et al. discussed the effect of tool path strategies and pocket geometry on surface roughness during pocket milling of mold steel DF2 using a carbide insert end mill. Three levels of tool path (one direction, back and forth, and spiral) and three levels of pocket geometries were used. According to their results, the parallel spiral cutting tool path strategy yielded the lowest surface roughness, and the grade of a pocket is directly proportional to its surface roughness [12]. Banerjee et al. used a morphed spiral tool path strategy to pocket medium carbon steel surfaces with different island geometries like square and circle and to minimize machining time under a cutting force constraint [13]. In another work, a morph spiral tool path was utilized to analyze tool coating thickness's influence on cycle time, surface roughness, tool wear, and material removal rate during pocket milling of AISI stainless steel 316 material [14].

CAD/CAM simulation software was used to simulate the pocket machining time in order to minimize the machining time because pocketing takes a lot of time [5]. Shafie et al. simulated the machining time of pocket milling using Master CAM software to determine the shortest machining time. Testing showed that three styles of machining strategies - high speed, parallel spiral, and zigzag- were more beneficial than other machining strategies [15].

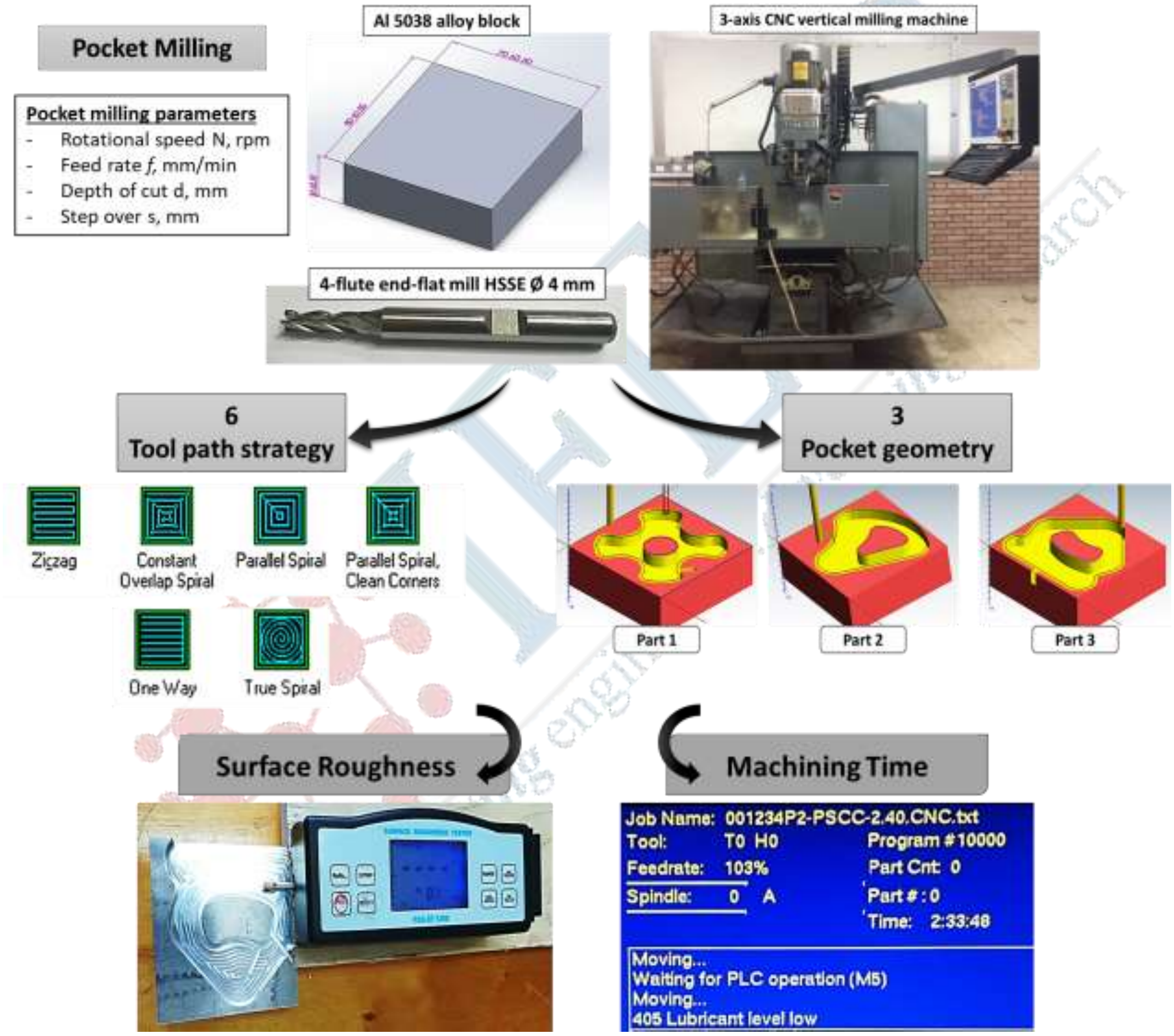
In the light of the above literature survey, it is found that most of the research work focuses on studying cutter path generation with the main aim of reducing the total cycle time and improving the surface finish quality. In the present study, an experimental investigation has been conducted to evaluate the effectiveness of different tool path strategies in the pocket milling of aluminum 5083 alloys. The experiments were executed at fixed cutting conditions using six tool path strategies: zigzag, constant overlap spiral, parallel spiral, parallel spiral with clean corners, true spiral, and one-way, generated by Master CAM program software. The impact of the pocket geometry has been incorporated into the problem, so three pocket geometries have different shapes, sizes, and contours, with varying shapes of interior islands being milled. The evaluation of pocketing strategy efficiency is based on the pocket machining time and the achieved surface quality. A comparison between actual CNC and CAM simulated machining times has also been discussed. Figure 3 illustrates the workflow done during this research.

II. EXPERIMENTAL PROCEDURE

A. Materials and Tooling

Aluminum alloys are the most commonly used material after steel in the industry due to their low density, high strength-to-weight ratio, good corrosion and fatigue resistance, and high material removal rate properties [7]. Commercially available Al 5083 alloy, which has potential applications in shipbuilding, vehicle bodies, mine skips, cages, and pressure vessels, has been used in the present work. Pocket milling experiments were conducted on a three-axis CNC vertical milling machine on Al 5083 alloy blocks with dimensions of 80 x 70 x 30 mm^3. The chemical composition and mechanical properties of the used material are shown in Table 1 (a) and (b), respectively.

As tools, 4-flute IZAR end-flat mill HSSE DIN 844N of 4 mm diameter and 30° helix angle were employed (Figure 2). The input cutting values for the material to be processed are given in **Error! Reference source not found.**. All experiments were performed using cutting fluid.



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Tool:      T0  H0               Program #10000
Feedrate:  103%                 Part Cnt  0
Spindle:    0   A               Part # : 0
                                Time:   2:33:48
Moving...
Waiting for PLC operation (M5)
Moving...
405 Lubricant level low
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Figure 1. Flow chart of experimental methodology

B. Experimental Setup and Pocket Milling Method

The current study investigates the impacts of different tool path strategies and pocket geometries on the surface roughness and machining time in pocket milling of Al 5083 alloy. The cutting parameters are kept at a constant value, while the variables are six levels of tool path strategies and three pocket geometries. Three pocket geometries extracted from the bibliography are selected and chosen on the basis of symmetric and non-symmetric closed curves with an interior island. Modern CAM software provides up to eight tool path strategies that can be used in pocket milling. This means that it would be beneficial in tool path planning to have more movements in the advantageous axis from the available alternatives. Accordingly, having longer paths and fewer tool stops during machining is preferable to save time [16].

Master CAM V 9.1, a commercial CAM software program, is used to select six different tool path direction strategies (zigzag, constant overlap spiral, parallel spiral, parallel spiral with clean corners, one-way, and true spiral) and generate the required G-codes for the CNC milling machine. NC codes are checked and simulated before being sent to the CNC milling machine. Each geometry is machined twice using each of the six selected tool path strategies. Prior to pocket milling tests, a facing process was performed on all the workpiece blocks to ensure surface flatness. Throughout the designated experiments, cutting parameters, tool diameter overlap of 50%, and tool movement start and end points are the same for all strategies.

The effectiveness of different tool path strategies and different pocket geometries is evaluated and compared in terms of machining time and surface roughness. Surface roughness (Ra) is measured using a Surface Roughness tester PCE- RT 1200 device. The Mean Roughness (Roughness Average Ra) is the arithmetic average of the absolute values of the roughness profile ordinates**.** Arithmetic mean roughness (Ra) is one of the most effective surface roughness measures adopted in common engineering practice. Five measurements in two directions, longitudinal and transversal, are conducted to obtain the average value Ra with a 0.8 mm cut-off and 4 mm sampling length.

Figure 2. Cutting tool used in experiments

Table 1. (a) Chemical composition and (b) Mechanical properties of Al 5083 alloy

(a) Chemical composition

Element	Al	Mg	Mn	Cr	Fe	Si	Zn	Ti	Cu	others
Weight %	93.99	4.18	0.873	0.0805	0.188	0.0946	0.239	0.0199	0.003	remainder

(b) Mechanical properties

Yield stress (Mpa)	Tensile strength (Mpa)	Elongation (%)	Hardness (HRC)
160	278	22	56.5

Table 2. Cutting conditions for pocket milling

Parameters	**value**
Cutting speed, v	60 (m/min)
Feedrate, f	1000 (mm/min)
Feed/tooth, f_t	0.16 (mm/tooth)
Depth of cut, d	1 (mm)
Step over, s	0.15 (mm)

III. RESULTS AND DISCUSSION

A. Machining Time

Machining time is a key factor contributing to the total costs of manufacturing processes. Moreover, machining time has an impact on a variety of other aspects such as gas emissions, consumed cutting fluid during wet machining, power consumption, etc. [2], [3]. Therefore, tool path and direction, in combination with the appropriate selection of cutting parameters, play a crucial role in machining optimization to minimize cutting time and costs. In this perspective, machining time has been investigated and compared throughout this work's theoretical and experimental machining times. Table 3 demonstrates the actual CNC machining time according to the data obtained from the experimental results and the machining time estimated from MasterCAM simulation results for each pocket geometry and tool path strategy. Figure 5 compares CNC actual machining time for different tools, all strategies, and pocket geometries. It can be noticed that the tool path strategy significantly impacts the actual machining time due to the amount of acceleration and deceleration as well as direction changes in the machine's movement.

Table 3. Machining time vs. tool path strategy and pocket geometry

Pocket Geometry	**Tool path Strategy**	**Zigzag**	**Constant Overlap Spiral**	**Parallel Spiral**	**Parallel Spiral, Clean Corners**	**One Way**	**True Spiral**
Part 1	MasterCAM® Simulation Time (min)	2:36:35	2:42:04	2:48:02	3:10:52	3:14:37	4:20:28
	Experimental Machining Time (min)	2:40:54	٣:٠١:٠٢	2:56:12	3:16:06	3:19:12	4:27:50
Part 2	MasterCAM® Simulation Time (min)	2:16:08	2:42:04	2:37:11	2:37:11	3:06:39	4:01:33
	Experimental Machining Time (min)	2:22:01	2:46:12	2:42:16	2:42:48	3:12:50	4:08:12
Part 3	MasterCAM® Simulation Time (min)	2:57:58	3:19:52	3:06:51	3:17:34	3:43:07	4:48:01
	Experimental Machining Time (min)	2:58:58	3:25:50	3:12:02	3:20:54	3:45:50	5:01:07

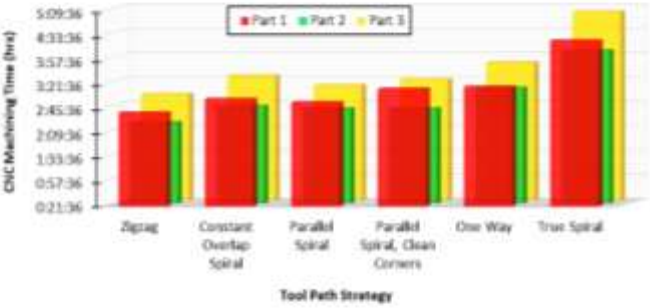

Figure 6. CNC actual machining time for different tool path strategies and pocket geometries

Both machining times obtained from the MasterCAM simulation program and CNC pocket milling operation are illustrated in Figure 6 (a), (b), and (c) for part 1, part 2, and part 3, respectively, for each tool path strategy. The Zigzag tool path strategy exhibited the least time, while the true spiral strategy had the most time for both simulation and actual machining time.

Figure 7. Comparison between simulation and actual machining time for (a) Part 1, (b) Part 2, and (c) Part 3.

This can be explained by the presence of smooth tool path sections that are almost free of accelerating and decelerating. Regarding the pocket geometry, it is observed that the second geometry gives the lowest machining time among other pocket geometries as it provides minimal smooth curvatures with continuous and consistent cutter engagement in its shape profile. In contrast, third pocket geometry takes the longest time to be machined owing to the symmetric and non-symmetric curves and profiles included in the geometry in addition to the complex shape of the interior island. Thus, selecting the correct tool path strategy concerning interior islands' geometry can facilitate continuous tool movement without slowing down or stopping during pocket milling, improving overall process performance.

The difference in time (ΔT) between experimental and simulated machining time has been calculated and compared by referring to Figure 6; the variation in machining time is considerably slight. In average terms, the simulated tool path is faster than the actual tool paths produced by the CNC milling machine. The first pocket geometry machined with constant overlap spiral strategy reveals the highest ΔT, about 19 minutes, and less ΔT for the third geometry machined by zigzag strategy, which is only one minute. Other tool path strategies, parallel spiral, parallel spiral with clean corners, one way, and true spiral, produce ΔT in the range of 2~8 minutes. The reason for this difference (ΔT) is that the idle time of the cutting tool path during the milling operation is relatively high. At the same time, simulation in the Master CAM package program accepts this time as cutting time.

On the other hand, CNC machining time represents the time spent using a cutting tool, including idle and cutting time, which is the main factor that affects the total machining costs. As a result, additional machining time is obtained. Therefore, it is paramount to consider both the actual and estimated machining time so that possible challenges to improve machinability can be overcome.

B. Surface Roughness

In industrial applications, product surface quality affects its functionality, such as wearing, contact, coating, and heat transmission, consequently affecting the quality and performance of mechanical parts and production costs [6]. Since pocket quality is evaluated based on its surface finish, it is vital to focus more on selecting the right tool path strategy during pocket milling.

Figure 8 shows the comparisons of surface topography of the pockets milled by different tool path strategies for (a) part 1, (b) part 2, and (c) part 3. In general, it is observed that the zigzag strategy produces higher machining marks when compared to the other tool path. This can be explained by pointing out that the zigzag movement of the cutting tool leads it to cut alternately along and then against the spindle direction, resulting in conventional and climb milling, respectively. This change in milling mechanisms results in the formation of uneven surface finish. Milling mechanisms include the repetitive entry and exit of each cutting edge into the workpiece material, which triggers excessive loads on the cutting tool. Therefore, repetitive mechanical load affects the chip formation as well as the produced surface texture. Also, it was noticed that evener surface topography was achieved when using the spiral tool path strategy. The efficient cutting occurs in the reverse direction of offsetting in the contour tool path strategy, i.e., from the inside toward the outside, which happens during spiral milling. This gives good stability to the work material as the cutting motion starts near the workpiece center [6].

Figure 9 shows the respective value of Ra for each tool path strategy and pocket geometry in (a) longitudinal and (b) transversal direction. On average, the parallel spiral tool path strategy produced the best surface finish, followed by true spiral and constant overlap spiral in both directions. The lowest roughness values (Ra) are obtained for the parallel spiral strategy of 0.1 mm, 0.11 mm, and 0.21 mm in the longitudinal direction and 0.15 mm, 0.19 mm, and 0.16 mm in the transversal direction for part 1, part 2, and part 3, respectively. The reason is that the machining mechanism in the parallel spiral strategy is a down milling process where the workpiece is fed in the same direction as the cutter's tangential velocity. The cutter enters the top of the workpiece and removes the chip that gets progressively thinner as the cutter tooth rotates, generating a better surface finish. The worst surface finish was determined when using a parallel spiral with a clean corners strategy as Ra was about 0.26 ~ 0.36 mm. The one-way tool path strategy generates a bad surface finish as well. It can be related to the longer cutting tool engagement with the workpiece surface during this strategy that may eventuate with excessive tool wear, leading to a rougher surface finish.

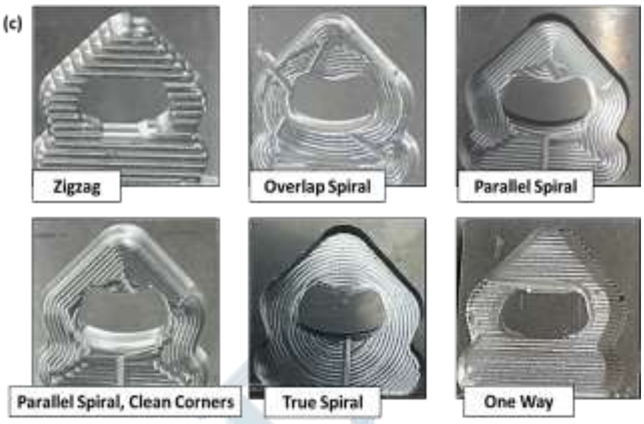

Figure 8. Surface topography of machined specimens at different tool path strategies (a) part 1, (b) part 2, and (c) part 3

In this context, the results of transversal and longitudinal roughness indicate that the best tool path strategy depends on the pocket geometry and the existence of islands that obstruct the path of the cutting tool. The influence also depends on the size and shape of the island contours and workpiece, the size of the used cutter, and cutting conditions. In general, we can't judge the finest tool path strategy since no specific tool path strategy can be applied to all workpieces on the same machine [20].

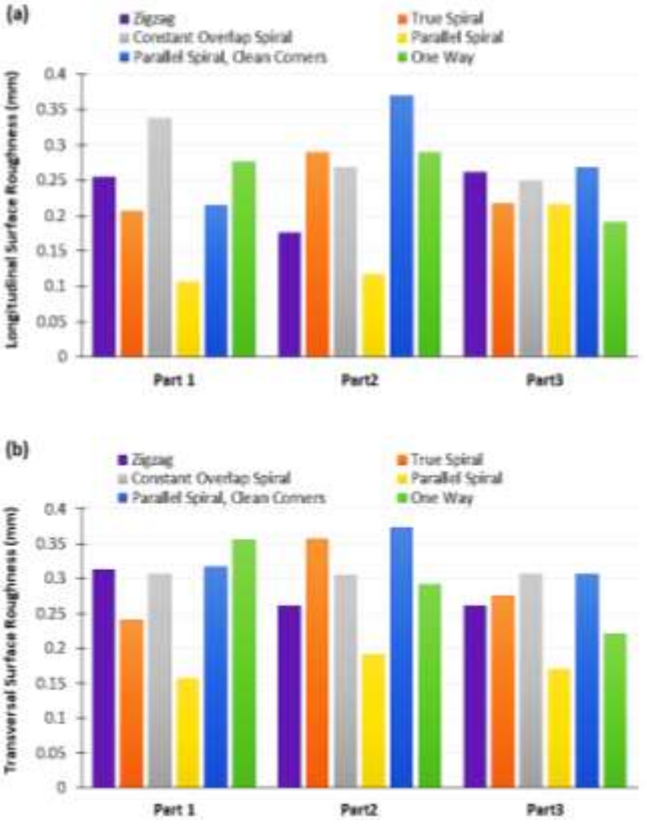

Figure 9. (a) Longitudinal and (b) transversal surface roughness for each geometry and strategy

IV. CONCLUSION

During this experimental study, three pocket geometries were selected, each machined using six tool path strategies generated via MasterCAM program. Based on the analysis of the experimental results, the following conclusions can be drawn:

- The tool path strategy and pocket geometry influence the surface quality and machining time during the pocket milling operation of Al 5083 alloy.
- Amongst the various tool path strategies utilized, the zigzag tool path strategy was found to be more favorable than other strategies as it provided minimum experimental and simulated machine time. True spiral strategy achieved the longest actual and simulated machining time for the three pocket geometries.
- When comparing CAM and CNC machining times, the Zigzag tool path strategy produced only one minute difference. The highest difference was about 19 minutes when using the constant overlap spiral strategy. For the other strategies, relatively small deviations ranged from 2~8 minutes (5%).
- It can be concluded that the parallel spiral strategy was the most effective tool path strategy and had higher precision to produce fine surface roughness based on experimental results. Parallel spiral roughness values were 0.1 mm, 0.11 mm, and 0.21 mm in the longitudinal direction and 0.15 mm, 0.19 mm, and 0.16 mm in the transversal direction for part 1, part 2, and part 3, respectively. The worst surface finish was obtained when using a parallel spiral with a clean corners strategy as Ra reached 0.35 mm.
- In terms of pocket geometry, it can be stated that pocket geometry, its shape, size, and contours, as well as interior island's existence, directly influence the surface roughness of the machined pocket. Summing up, the adequate choice of tool path strategy to mill a specific geometry can improve the surface quality and overall process performance.

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