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SELECTION OF EFFICIENT CUT PATTERN FOR SIMPLE POCKET MACHINING IN TRADITIONAL MILLING

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ABSTRACT

Product quality and process efficiency are the two major factors in competitive manufacturing. Currently, most of the milling operations in die and mold manufacturing are based on experienced-based approaches, which need a lot of time and effort. To reduce the time and effort needed in the traditional approaches, cutting parameters should be selected on a scientific basis. In mold and die manufacturing, estimation of the machining time of tool paths is a pre-requisite for planning the machining process. Mainly two types of cut patterns can be observed in end milling operation: direction parallel and contour parallel. Each of these types of cut patterns has its own benefits and limitations. Besides, the machining time is different for each of these cut patterns. In this work, models for different tool path patterns have been developed to calculate machining time. Different cut patterns were then compared based on the calculated machining time. The developed models were later validated by experimental results.

Keywords: *Cut Pattern, Direction Parallel Path, Contour Parallel Path, Tool Path Length.*

1. Introduction

In mold and die manufacturing, estimation of the machining time of tool paths is a pre-requisite for planning the machining process. Machining time is computed by dividing the total tool path length by its feed rate. Mainly two types of cut patterns can be observed in end milling operation: direction parallel and contour parallel. Zig and zig-zag are two types of direction parallel tool paths, whereas spiral-in and spiral-out are the two types of contour parallel tool paths. Each of these types of cut patterns has its own benefits and limitations. Besides, the machining time is different for each of these cut patterns. Maintaining the part quality requirement, one of the cut patterns need to be selected based on all the merits and demerits of the different techniques. The four types of cut patterns are shown in Fig 1-2.

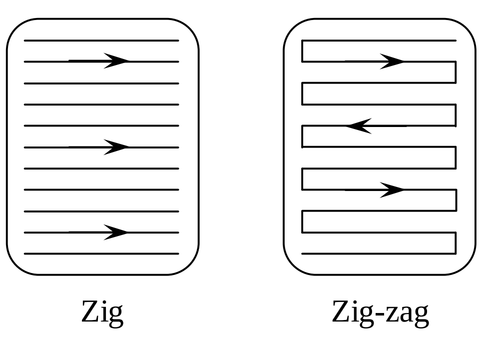

Fig. 1 Direction-Parallel Tool Path Pattern

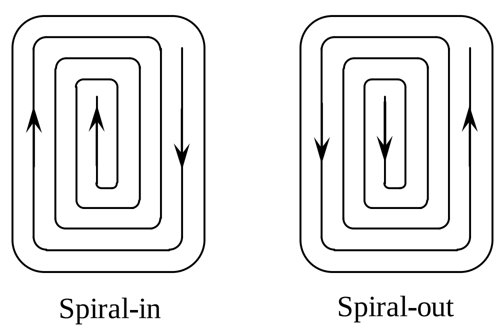

Fig. 2 Contour-Parallel Tool Path Pattern

Most of the available research results [1-3] on direction-parallel area milling focus on the zigzag pocketing problem. Especially Held [1, 3] reported serious investigations on optimizing zigzag pocket machining. The approach Voronoi Diagram, was pioneered by Persson [4], who proposed partitioning the pocket area into independent sub-areas and determining the points of intersection of the boundary or offset curves and the bisector skeleton. To improve the efficiency of the initial algorithm [4] and include technological issues, proximity maps that had been proposed by Held [3], Guyder [5] addresses some guidelines for CPO tool path optimization and a tool path linking algorithm. Based on the guidelines, Held et. al. [3] presented an algorithm for CPO tool path generation for pocket machining based on the proximity maps, Voronoi diagram. To machine a pocket

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containing islands by consistent CPO tool path, he discusses a linking procedure requiring a spanning tree of the planar graph of the monotonic pouches. Park and Chung [6] proposed a CPO tool path linking algorithm accommodating the Guider's guidelines (minimization of slotting, tool retractions and drilling holes). Although, their algorithm considers all the requirements, it does not fully optimize all of them because some of them cause conflicts. To cope with the uncut problem, Park and Choi [7] proposed an algorithm generating the clean-up TPE s. Later they [8] tried to improve the above algorithm by removing local invalid loops and reduce uncut region. Choi and Kim [9] proposed the approach (pixel) based on 3D cutting simulation model using pixels to compute the boundary curve and the offset curves from it. Uncut region deals with the residual material in the pocket which is left behind by the cutting tool. The approaches that have been proposed to reduce the uncut region in CP are Voronoi Diagram [3], constrained tool path generation [10] which were subsequently eliminated by adding clean up cuts [8]. Detecting the uncut region was simplified by detecting the pixels lying outside the cutter swept area, in a pixel based approach [9]. In Spiral pattern, uncut region had been avoided by dynamic offsetting approach [11]. The change in the tool path length along with the tool path interval had been shown to reflect the improvement in the productivity by Park and Choi [8]. Maneul et al. [12] generated spiral tool path based on dynamic computation of optimal offset curves. Maneul et al. [12] also reported the reduction in the machining time by avoiding short contour segments and tool retractions. Bieterman and Sandstorm [13] reported a 30% reduction in the machining time with their spiral pattern which included feed rate scheduling. The literature dedicated to minimizing tool retraction [3, 4], drilling holes and slot cuts [10] also indirectly attempts to reduce the machining time. Kim et. al. proposed an optimized contour parallel tool-path for 2D milling with flat end mill, however, no comparison has been found against direction parallel tool path [14]. Midany et. al. [15] compared direction parallel and contour parallel toll path patterns for rough cut machining of sculpture surfaces. It was found that the optimal tool path pattern varies on dependent on part geometry, physical characteristic of used machine tool and cutting conditions. Different cut patterns for milling have been considered by Kim [16] at constant cutting material removal rate which was implemented for 2D contiguous end milling operation. Additional tool path segments were appended to the basic tool path obtained by geometric shape by using a pixel-based simulation technique. All of the mentioned works however directly address one particular issue which is the minimizing machining time, though product quality due to different types of cut patterns have never been considered which is a prime requirement in modern manufacturing.

In this paper, different cut patterns are considered to machine a simple 2D pocket. Mathematical models were developed using geometric consideration that allows quick calculation of machining time. The four different patterns have been compared based on machining time so that the most efficient cut pattern can be selected maintaining the product quality. So, productivity and quality have been considered simultaneously in the present work.

2. Model Formulation

Four types of cut pattern have been analyzed. These patterns are- Zig, Zigzag, Spiral-in and spiral-out in this research work. Each of these patterns has an algorithm which is essential to calculate the total tool path length. Total machining time is then calculated by dividing the total time by feed rate. To reduce the extra time for frequent tool retraction, only one tool is considered to machine the entire pocket area. The diameter of the selected tool is equal to the diameter of pocket corners.

2.1 Zig

In this cut pattern, for a given length and width the cutter moves a certain distance across the width. Then the cutter is withdrawn and is placed in initial point for next cutting. The process stops when the job is completed. Total tool path length is computed by the addition of each tool path length.

In Fig 3, Length of each of the tool path can be calculated as:

$$TPL = l - d \qquad (1)$$

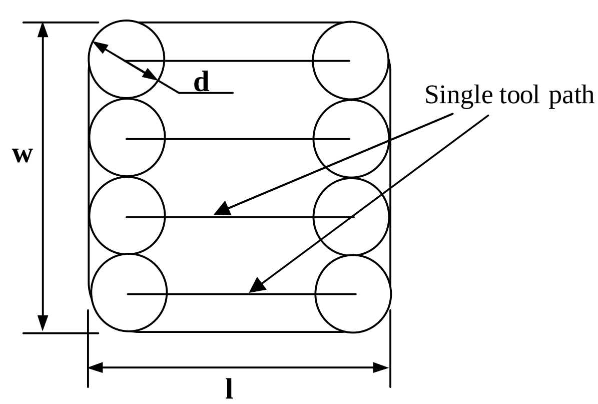

Fig. 3 Tool Path in Zig Pattern

where, TPL = Tool path length of each segment
l = Length of the area to be machined
d = Tool diameter

Total number of tool paths to cover the width of the job will vary according to the side step or radial depth of cut. For a step size of full diameter of the cutter,

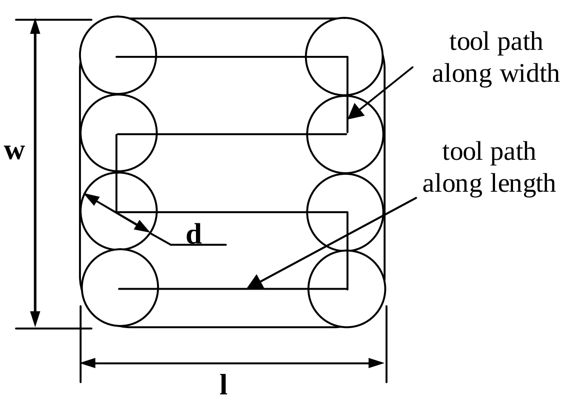

Fig. 4 Tool Path in Zig-zag Pattern

$$No\ of\ paths = \frac{width\ of\ the\ area}{tool\ diameter} = \frac{w}{d} \quad (2)$$

where, w = width of the area to be machined

For a step size of half diameter of the cutter,

$$No\ of\ paths = \left(\frac{w}{d}\right)*2-1 \quad (3)$$

For a step size of quarter diameter of the cutter,

$$No\ of\ paths = \left(\left(\frac{w}{d}\right)*2-1\right)*2-1 \quad (4)$$

To remove the remaining material at two sides across the width, i.e., $(w-d)$ for each side will ultimately increase the total tool path length. So,

$$Total\ Tool\ Path\ Length = Length\ of\ each\ tool\ path * Total\ number\ of\ tool\ paths + 2*(w-d) \quad (5)$$

It can be mentioned here that this formulation to calculate total tool path length ignores the tool retraction time. This tool retraction time varies machine to machine and hence not wise to incorporate any exact amount of time. For machine tools with high rapid positioning feed rate, this time can be considered negligible for a part requiring larger machining time. Formulation for zig-zag pattern also considers the same.

2.2 Zig-zag

In this pattern, for a pocket of given length and width, the cutter moves a certain distance across the length. Then it moves across by an amount of radial depth of cut (Fig 4). Next the cutter again moves back to a distance equal to the length of the job. This sequence continues until the tool reaches the maximum width of machining area. The process differs from zig process is that in this process the cutter is not withdrawn each time. Like the zig pattern, total number of tool paths to cover the width of the job will also vary according to the side step or radial depth of cut. Length of each of the tool path can be calculated as:

$$TPL = l - d \quad (6)$$

where, TPL = Tool path length of each segment
l = Length of the area to be machined
d = Tool diameter

Total number of tool paths to cover the width of the job will vary according to the side step or radial depth of cut.

For a step size of full diameter of the cutter,

$$No\ of\ paths = \frac{width\ of\ the\ area}{tool\ diameter} = \frac{w}{d} \quad (7)$$

where, w = width of the area to be machined

For a step size of half diameter of the cutter,

$$No\ of\ paths = \left(\frac{w}{d}\right)*2-1 \quad (8)$$

For a step size of quarter diameter of the cutter,

$$No\ of\ paths = \left(\left(\frac{w}{d}\right)*2-1\right)*2-1 \quad (9)$$

For a step size of full diameter, half diameter and quarter diameter of the cutter, number of paths is exactly the same as that of zig pattern. However, due to cross feed motion, the tool path will increase by an amount of $[(Total\ number\ of\ tool\ paths - 1)*radial\ depth\ ]$. To remove the remaining material at two sides across the width, i.e., $(w-d)$ for each side will ultimately increase the total tool path length. So, total tool path length including the material removal across the width can be calculated as:

$$Total\ Tool\ Path\ Length = Length\ of\ each\ tool\ path * Total\ number\ of\ tool\ paths + \begin{pmatrix} Total\ number \\ of\ tool\ paths - 1 \end{pmatrix} * radial\ depth\ of\ cut + 2*(w-d) \quad (10)$$

2.3 Spiral-in

For this pattern, tool starts cutting from the outer boundary of the area to be machined. Instead of the patterns either along the length or along the width, the tool moves along the contour of the area (Fig 5). That means, the tool path will alternately change the direction along length and width. In this research, a complete cycle around the contour is considered as one path which is used to calculate total tool path length. Each cycle of the tool path has four tool path segments – two along the length and two along the width. Except the first and last cycle, all other segments of each cycle follow the same algorithm (considering *l*=*w*).

For the first cycle, the tool path length is:

$$TPL_s = 4*(l-d)-r_d \tag{11}$$

For the last cycle, the tool path length is:

$$TPL_f = 4*(l-d)-(i-1)*8*r_d + r_d \tag{12}$$

For rest of the cycles, the tool path length is

$$TPL_m = 4*(l-d)-(i-1)*8*r_d \tag{13}$$

here l = length and width of the pocket
d = cutter diameter
r_d = radial depth of cut
i = number of tool path cycle

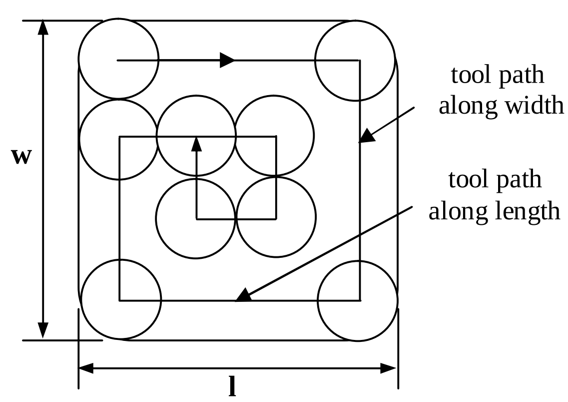

Fig. 5 Tool Path in Spiral-in Pattern

For a step size of full diameter of the cutter,

$$No\ of\ cycles = \left(\frac{l}{d}\right)/2 \tag{14}$$

For a step size of half diameter of the cutter,

$$No\ of\ cycles = \left(\frac{l}{d/2}\right)/2-1 \tag{15}$$

For a step size of quarter diameter of the cutter,

$$No\ of\ cycles = \left(\left(\frac{l}{d/2}\right)/2-1\right)*2 \tag{16}$$

No extra finishing cut along the walls is required in this case. As a result, the total tool path length can be written:

$$\begin{aligned} Total\ Tool\ Path\ Length &= (4*(l-d)-r_d) \\ &+ (Total\ number\ of\ tool\ paths - 1) \\ &*(4*(l-d)-(i-1)*8*r_d) \\ &+(4*(l-d)-(i-1)*8*r_d + r_d) \end{aligned} \tag{17}$$

2.4 Spiral-out

For this pattern, tool starts cutting from the center of the area to be machined. Like the spiral-in pattern, the tool moves along the contour of the area (Fig 6). That means, the tool path will continuous change the direction along length and width. A complete cycle around the contour is considered as one path which is used to calculate total tool path length. Like spiral-in pattern, each cycle of the tool path has four tool path segments – two along the length and two along the width. Except the first cycle, all other segments of each cycle follow the same algorithm.
For the first cycle, the tool path length is:

$$TPL_s = 5*r_d \tag{18}$$

For rest of the cycles, the tool path length is

$$TPL_m = r_d(8*i-4) \tag{19}$$

There will always be an extra segment at the very end with a value of r_d .

For a step size of full diameter of the cutter,

$$No\ of\ cycles = \left(\frac{l}{d}\right)/2 \tag{20}$$

where, l = length of the area to be machined.

For a step size of half diameter of the cutter,

$$No\ of\ cycles = \left(\frac{l}{d/2}\right)/2-1$$

For a step size of quarter diameter of the cutter,

$$No\ of\ cycles = \left(\left(\frac{l}{d/2}\right)/2-1\right)*2 \tag{21}$$

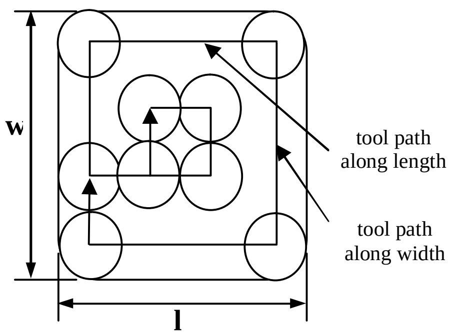

Fig. 6 Tool Path in Spiral-out Pattern

Unlike the zig and zig-zag patterns, no extra finishing cut along the walls is required in this case. As a result, the total tool path length can be written as:

$$\begin{aligned} &\textit{Total Tool Path Length} = 5 * r_d \\ &+ (\textit{Total number of tool paths} - 1) \\ &\quad * (r_d (8 * i - 4)) + r_d \end{aligned} \qquad (22)$$

3. Verification of the Proposed Model

Fig 7 shows a four-sided pocket with geometric dimensions, which is taken as a sample part to be machined by using end mills. It is a rectangle pocket with planar bottom and vertical walls. The inner area of the pocket to be cut is 54 mm X 54 mm. Due to few limitations in the milling machine used in this experiment; a constant feed rate has been employed for machining three different types of material. Plastic, Aluminium and mild steel are the three types of material

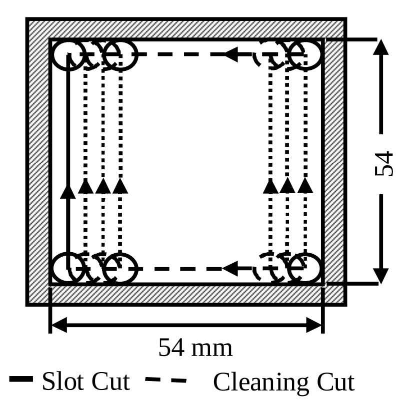

Fig. 7 Sample Pocket for Verification Tests

machined using High Speed Steel (HSS) cutters of diameter 12 mm and 6 mm. For plastic, 6 mm dia cutter was used with radial depths of 3mm (d/2) and 1.5 mm (d/4). For aluminium and mild steel, 12mm dia cutter was used with radial depths of 6mm (d/2) and 3 mm (d/4). In pocket machining, three different cuts combine a complete cut; they are slot cut, peripheral cut and the cleaning cut. Machining starts with slot cut having the total tool diameter engaged in cutting. The thick black line represents the slot cut in this pocket machining.

For direction parallel tool paths, there is only one slot cut in complete pocket machining, whereas, in contour parallel tool paths, a complete cycle around the four sides is slot cut. It is the initial cut in the pocket milling. Peripheral cut, the dotted lines are the tool paths with the same radial depth of cut, which is the primary tool path. Most material of the pocket is removed and this cutting process takes the longest time. Cleaning cut, the dashed lines represents the last milling to the pocket. After the first two millings are finished, there will be still some residual material on the side wall with the width, which is called scallop and usually not permitted by the tolerance requirements. Therefore, an extra milling is required to clean up the scallop on the wall. However, this cut is only applicable to direction parallel tool paths, not for contour parallel tool paths.

The sequence of machining this pocket is that the first step is slot cut, then peripheral cut and the last step is the cleaning cut (if required). Therefore, the total machining time considered in the current study is the summation of the time taken by each of these three cuts for direction parallel machining and first two for contour parallel machining. A constant feed rate has been maintained throughout the process for all different materials as well as cutter. The value of the feed rate is 4.5 in/min, i.e., 114.3 mm/sec.

Table 1 shows the total tool path length for various combinations of material and radial depth of cut. From Table 1, we can realize that the tool path length for different cut pattern is different. However, for spiral-in and spiral out patterns, the lengths are same for a square pocket. Zig-zag pattern always gives the highest value of tool path length due to the cross feed motions. Using these calculated tool path lengths, the machining time for each material-cutter combination has been calculated by dividing the total tool path length by used feed rate. Actual machining time was captured during the cutting motion of each test cut. The actual machining time has been compared to the theoretical one and the deviation percentage has been calculated to check the validity of the proposed model. Table 2 shows the theoretical and actual machining time comparison for different cutters and cut patterns.

4. Results and Discussions

According to the results of the machining time comparison (Table 2), the contour parallel tool paths are more efficient compared to the direction parallel tool paths. Extra finishing cuts for zig and zig-zag patterns are mainly responsible for the inefficiency of direction parallel tool paths. Moreover, tool retraction time which is considered negligible in the formulation also makes the direction parallel tool paths less productive compared to the contour parallel tool paths.

Although both spiral-in and spiral out tool paths gives equal machining time using the developed model, experimental results show that total machining time required for spiral-out compared to spiral-in pattern. The deviation mainly resulted from the amount of material removal in total machining. For spiral-out cut, cutter starts at the very center point of the area to be machined, and for only the first cut (smallest path segment of complete cut) the full area of the cutter is engaged with the material. After that, cutter is engaged by an amount of radial depth of cut.

Table 1: Total Tool Path Length (mm) for different Cut Patterns

	Material	Plastic with 6 mm cutter		Aluminium with 12 mm cutter		Mild Steel with 12 mm cutter	
	Radial depth (mm)	**d/2 (3 mm)**	**d/4 (1.5 mm)**	**d/2 (6 mm)**	**d/4 (3 mm)**	**d/2 (6 mm)**	**d/4 (3 mm)**
Cut pattern	Zig	912	1680	420	714	420	714
	Zig-zag	960	1728	462	756	462	756
	Spiral-in	771	1434	372	678	372	678
	Spiral-out	771	1434	372	678	372	678

Table 2: Machining time (min) comparison for different cut patterns

Radial Depth	**Machining Time (min) for Plastic** d/2 (3 mm)			d/4 (1.5 mm)		
Cut Pattern	**Model**	**Experiment**	**% error**	**Model**	**Experiment**	**% error**
Zig	7.98	7.717	3.4	14.7	14.504	1.35
Zig-zag	8.4	8.25	1.82	15.12	14.92	1.34
Spiral-in	6.75	7.044	4.2	12.55	12.738	1.48
Spiral-out	6.75	6.99	3.5	12.55	12.24	2.53
Radial Depth	**Machining Time (min) for Aluminium** d/2 (6 mm)			d/4 (3 mm)		
Cut Pattern	**Model**	**Experiment**	**% error**	**Model**	**Experiment**	**% error**
Zig	3.67	3.79	3.2	6.25	6.53	4.3
Zig-zag	4.04	4.19	3.6	6.61	6.88	3.9
Spiral-in	3.25	3.43	5.2	5.93	6.18	4.1
Spiral-out	3.25	3.419	4.9	5.93	5.996	1.1
Radial Depth	**Machining Time (min) for Mild Steel** d/2 (6 mm)			d/4 (3 mm)		
Cut Pattern	**Model**	**Experiment**	**% error**	**Model**	**Experiment**	**% error**
Zig	3.67	3.81	3.7	6.25	6.58	5
Zig-zag	4.04	4.23	4.5	6.61	7.08	6.6
Spiral-in	3.25	3.51	7.4	5.93	6.31	6
Spiral-out	3.25	3.48	6.6	5.93	6.27	5.4

Table 3: Comparison of Surface Roughness (mμ) for different Cut Patterns

Surface Finish (mμ) for Plastic								
Cut Pattern	**Zig**		**Zig-zag**		**Spiral-in**		**Spiral-out**	
Radial Depth	d/2	d/4	d/2	d/4	d/2	d/4	d/2	d/4
	3.48	3.41	3.52	3.39	3.88	3.65	3.46	3.38
Surface Finish (mμ) for Aluminium								
Cut Pattern	**Zig**		**Zig-zag**		**Spiral-in**		**Spiral-out**	
Radial Depth	d/2	d/4	d/2	d/4	d/2	d/4	d/2	d/4
	4.56	4.38	4.42	4.41	4.79	4.70	3.82	3.67
Surface Finish (mμ) for Mild Steel								
Cut Pattern	**Zig**		**Zig-zag**		**Spiral-in**		**Spiral-out**	
Radial Depth	d/2	d/4	d/2	d/4	d/2	d/4	d/2	d/4
	6.21	6.09	6.16	6.10	6.55	6.32	5.93	5.81

However, for spiral-in pattern, cutter starts travel from the outer corner of the machining area. For a complete cycle of the total tool path (largest of all the cycles), the full diameter of the cutter is engaged with material. Hence, large amount of force is exerted on the cutter for a longer time period compared to spiral-out pattern. As a result, due to some limitations of the machine used for this research work, the travel rate of the cutter is little slower than the designated feed rate. It can also be observed from the machining time comparison table (Table 2) that the error percentage is much higher in mild steel compared to that in plastic and aluminium. This is also resulted from the machine limitation where it slower down the cutter travel rate for harder material. However, Table 2 shows that the error percentage for all type of patterns and materials is within 10% of the machining time values. This shows the validity of the proposed models for different cut patterns. Alongwith the machining time, surface roughness is also a very important factor in selecting the cut pattern in simple milling. To serve this purpose, surface roughness was also measured for all the machined parts with different cut patterns.

Table 3 shows that the surface finish is much better in spiral-out pattern compared to the other three. Spiral-in pattern has the worst surface finish as the outer wall is machined with full cutter diameter which resulted higher load on cutter and hence cutter deflection. Due to the extra finish cut for zig and zig-zag patterns, the side walls have better surface finish compared to the first cut with full cutter diameter.

5. Conclusions

In mold and die manufacturing, the estimation of the machining time of tool path is very important in planning machining processes and balancing them. In this research work, total four types of tool path pattern have been considered in this regard. The patterns are zig and zig-zag for direction parallel patterns and spiral-in and spiral-out for contour parallel paths. Models for calculating total machining time have been developed to compare the machining times for the mentioned four types of cut patterns. Results from developed models are then compared with the experimental results to show the validity of the proposed models. From the theoretical and experimental results, it can be concluded that the spiral-out pattern gives the best result in machining a simple pocket with vertical walls. Only one cutter having the same diameter as the corner radius of the pocket can be used to eliminate/reduce the tool retraction time. The spiral-out pattern also causes negligible chatter and vibration due to less cutter-part contact area during machining.

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Nomenclature

Symbol	Meaning	Unit
l	length of the area to be machined	mm
w	width of the area to be machined	mm
d	cutting tool diameter	mm
r	radial depth of cut	mm
i	number of tool path cycle	
TPL	tool path length of each segment	mm

