

Investigation of tool engagement and cutting performance in machining a pocket

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Abstract. This study investigates the variation of tool engagement for different profile of cutting. In addition, behavior of cutting force and cutting temperature for different tool engagements for machining a pocket also been explored. Initially, simple tool engagement models were developed for peripheral and slot cutting for different types of corner. Based on these models, the tool engagements for contour and zig zag tool path strategies for a rectangular shape pocket with dimension 80 mm x 60 mm were analyzed. Experiments were conducted to investigate the effect of tool engagements on cutting force and cutting temperature for the machining of a pocket of AISI H13 material. The cutting parameters used were 150m/min cutting speed, 0.05mm/tooth feed, and 0.1mm depth of cut. Based on the results obtained, the changes of cutting force and cutting temperature performance there exist a relationship between cutting force, cutting temperature and tool engagement. A higher cutting force and cutting temperature is obtained when the cutting tool goes through up milling and when the cutting tool makes a full engagement with the workpiece.

1. Introduction

Tool engagement can be defined as the portion of the tool that engages with the workpiece during machining process. In pocket machining process, the engagement angle is an important cutting parameter that affects the cutting forces and cutting temperatures. The engagement is constant during straight cutting. However, when the cutting tool turns along a corner profile of the pocket, variation in engagement occurs. As a consequence, it will affect the surface finish of the machined surface. Many researches have looked into the problem of fluctuation of the cutting force caused by variation of engagement. One of early study of tool engagement was done by Kramer [1]. He developed an algorithm to detect the minimal engagement for pocket with island using zig zag tool path. As improvement to the Kramer technique, the tool path modification technique was introduced by later researchers to maintain the engagement angle during machining especially at the corners. Most of the studies focused on modification of tool path strategy to achieve a constant tool engagement and hence indirectly maintaining the cutting force. One of the earliest studies in tool path modification was by Stori et al. [2]. They introduced an offset tool path to maintain engagement during convex profiling of pocket. Practically, this method is unreliable because in a pocketing operation, the tool travels in various profiles to make a pocket such as convex, triangle etc. In addition, the approach is suitable for



rough cutting only as excessive left and additional cutting is required. However, this approach is distinctive and as initial step for other researchers to make improvement in pocketing operation. Due to the drawbacks of the Stori approach, Ibaraki et al. [3] presented a new algorithm for tool path modification known as backward and forward tool path generation. The application of forward tool path with the same value feed rate was compared with the cutting force. Another improvement regarding tool path modification to maintain tool engagement had been made by Uddin et al. [4] whom expended the Ibaraki approach by presenting an algorithm for semi-finishing cutting. From the results, cutting forces can be maintained throughout the cutting process. Apart from that, Dumitrache [5] had improved the Ibaraki backward algorithm by setting the reference value of tool engagement angle to 20° . As an improvement to previous methods, by applying this algorithm, machining time can be reduced. However, this method is suitable for only rough machining process.

Cutting temperature is closely related to cutting forces. Primarily, the rise of cutting temperature would affect cutting tool and lead to bad surface finish. For pocketing operations, the cutting tool needs to travel to make both straight and cornering cuttings. At the corner, the spindle speed needs to slow down to change direction of the tool. The changes in spindle speed and feedrate during the corner cutting operation thermally affects the work material and cutting tool Held et al. [6]. The investigation of tool engagement and cutting temperature not much explore by researcher. The recent study conducted by Riza [7]. The study conducted is specifically for contour tool path strategy only.

Hence, this study intended to investigate the behavior of cutting force and cutting temperature for different tool engagements in end milling process. Tool engagements model were developed for different tool path strategies. The relationship between tool engagement and cutting forces and cutting temperature was analyzed.

2. Experimental procedures

Experiments were conducted to investigate the effect of different tool engagements on cutting force and cutting temperature for the machining of a rectangular pocket with dimension 110 mm x 80 mm. Two types of tool path strategies were used in this study; contour and zig zag tool path strategy. The cutting parameters used for this experiment is shown in table 1. The machining operation was done by using CNC Vertical Machining Centre (VMC) by Mazak Nexus VCN 410-II. A Kristler 9257B dynamometer was attached to the workpiece and that supported by a charge amplifier and signal conditioning to measure the cutting force. The cutting temperature was measured using infrared thermal camera ThermoPro TP8. The IrAnalyzer software was used to record the temperature as well as to analyse the thermal image. To perform the machining operation, CoroMill 490 cutting tool with coated carbide insert was used. The tool diameter was 20 mm with two indexable insert positions. The two types of tool path strategies used for the machining the pocket was the contour and zig-zag tool path strategies.

Table 1. Cutting Parameters

Tool Path Strategy	Cutting Speed	Feed Per Tooth	Depth of Cut
Contour tool path strategy	150m/min	0.05mm/tooth	0.1mm
Inclination tool path strategy	150m/min	0.05mm/tooth	0.1mm

3. Results and Discussion

3.1 Tool engagement modeling

In modeling the tool engagement, two types of cutting were considered which were slotting and peripheral cuttings. Slotting is when the radial depth of cut or step over of the path is the same as the cutting tool diameter. During slotting, half of the cutting tool circumference is engaged with the

machining workpiece. In this case, the cutting tool makes a full engagement with the workpiece. Entry angle for slotting is zero degree and exit angle 180°. Peripheral cutting is when the radial depth of cut is less than cutting tool diameter. Compared to slotting, smaller portion of the cutting tool circumference is engaged with the workpiece. The amount of tool engagement depends on radial depth of cut as shown in Figure 1. The engagement angle for straight cutting can be obtained as discussed by Tsui et al. [8].

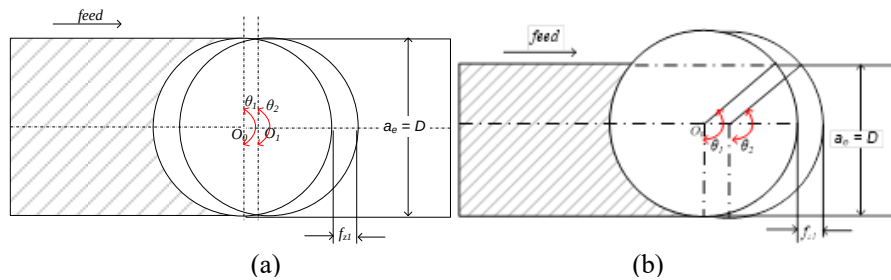


Figure 1. Tool engagement for straight cutting

In machining a pocket, the tool maintains full engagement along a straight path. However, when it turns 90° direction, the angle is reduced. It depends on the amount of feed per tooth and radial depth of cut of the path. However, the value of tool engagement angle remains constant for the case of radial depth of cut less than diameter of cutting tool. The value of engagement angle when the tool turns 90° corner is given by the following relationship;

$$\theta = 90 + \cos^{-1}\left(\frac{r - f_{z1}}{r}\right) \quad (1)$$

Then, the engagement increases until it reaches 180° again where the value of $(r - (f_{z1} + f_{z2} + \dots + f_{zn}) = 0)$ as in Figure 2. The increasing of engagement angle depends on the position of cutting tool in which the value of feed per tooth is;

$$\theta = 90 + \cos^{-1}\left(\frac{r - (f_{z1} + f_{z2} + \dots + f_{zn})}{r}\right) \quad (2)$$

$$f_{z1} + f_{z2} + \dots + f_{zn} < 10 \text{ (for } D=20 \text{ mm)}$$

$$f_{z1} = f_{z2} = \dots = f_{zn} = f_z$$

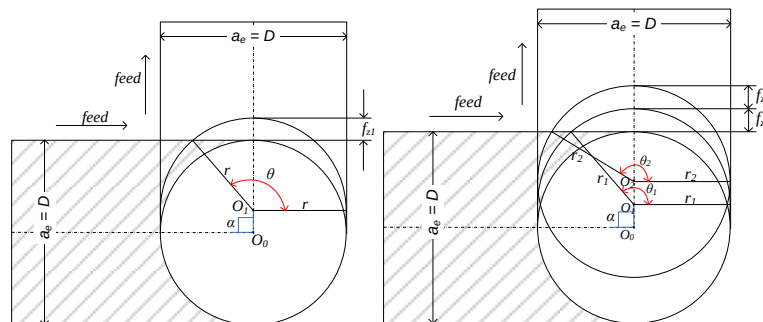


Figure 2. Tool engagement after 90° turn

For the case of less than 90° corner, the engagement depends on the angle of turning corner (α) as shown in Figure 3. The radial depth of cut decreased after the tool changes direction. Tool engagement

starts to vary at the on-set of cutting and then increases until the radial depth of cut is equal to the diameter of cutting tool. Radial depth of cut for can be determined by:

$$a_e = f_z \tan \alpha \quad (3)$$

Then, tool engagement can be calculated as:

$$\text{if } a_e \leq r$$

$$\theta = \cos^{-1}(1 - (a_e/r)) \quad (4)$$

$$\text{if } a_e > r$$

$$\theta = 90 + \sin^{-1}(a_e/r - 1) \quad (5)$$

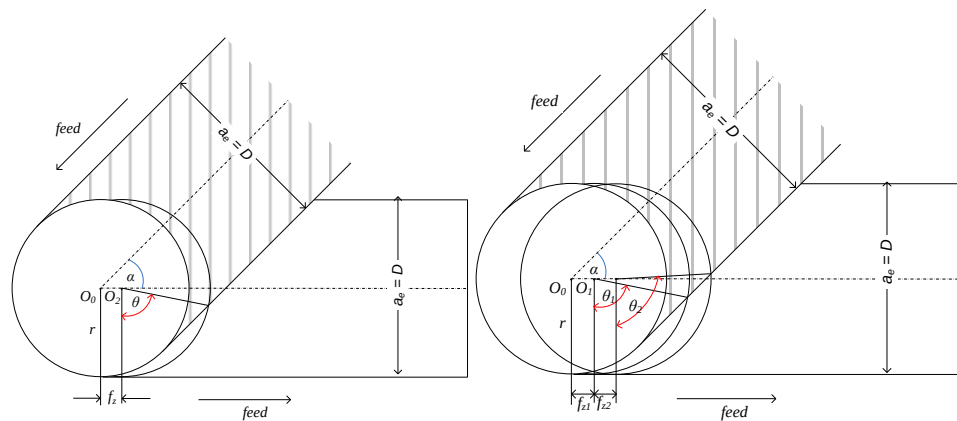


Figure 3. Tool engagement after less 90° turn

The calculated amounts of tool engagement during tool path strategies were plotted in the graph. Tool engagement angle was calculated by assuming that the first tooth of the cutting tool engages at the start of the circumference of radial depth of cut. The calculation of tool engagement angle is based on cutting tool with 20 mm diameter and 0.05 mm/tooth of feed. figure 4 and figure 5 shows the changes of engagement during contour and zig-zag tool path strategy respectively. For contour tool path strategy, the tool engagement remains constant during straight cutting. The changes occurred when the tool changes its direction.

For contour tool path strategy, there are sharp changes of tool engagement angle when the cutting tool turns 45° corner and when the tool enters to the slotting operation. For zig zag tool path strategy, the engagement angle changes alternately when the cutting tool changes its direction from full (100%) engagement to 75% engagement.

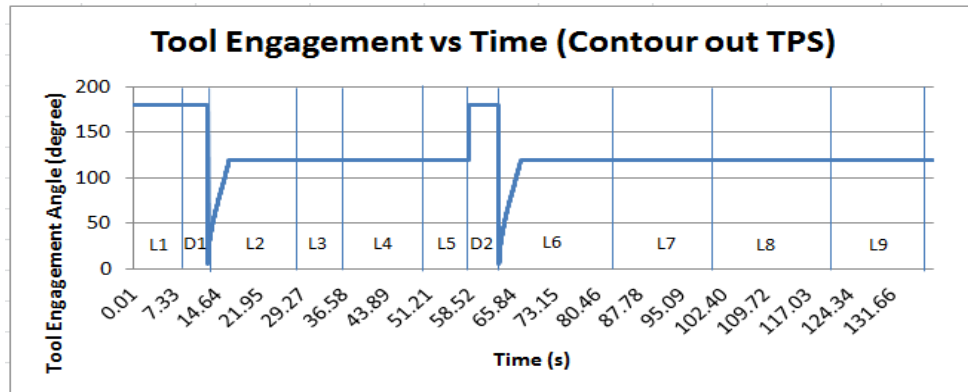


Figure 4. Tool engagement angle for contour tool path strategy

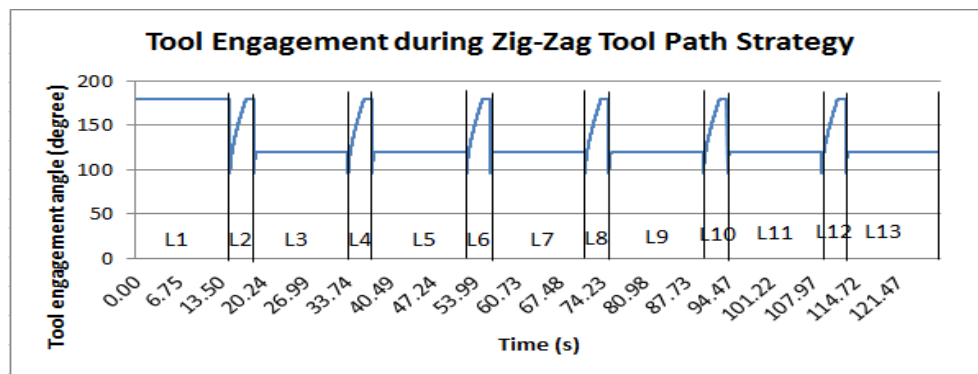


Figure 5. Tool engagement angle for zig zag tool path strategy

3.2 Cutting force and cutting temperature

The graph in Figure 6 shows the cutting force and cutting temperature for the contour tool path strategy. The cutting force and cutting temperature is the highest along L1 compared to the rest of the cutting process. This is due to the full engagement (180°) between the cutting tool and workpiece. In milling operation, when tool makes a full engagement with the workpiece, the cutting tool experiences both up milling and down milling. Chip thickness is zero at the starting and at the end of the process. Maximum chip thickness occurs in the middle of the process. The changes of tool engagements occur every time the tool changes its direction. The engagement angles for L2 to L4 and L6 to L9 is the same which is 120° . However, the cutting tool experiences down milling during L2, L3, L6 and L7. When entering L4, L5, L8 and L9, up milling occurs. From the graph, the cutting force is higher when the cutting tool transverses along the up milling path compared to down milling path. The same trend can also be seen for cutting temperature. Theoretically, the cutting forces in up-milling are higher compared to down-milling. For up milling, chip thickness is zero at the start of the process whereas for down milling chip thickness is zero at the end of the tool rotation. In up-milling, the cutting tool rotation is in the opposite direction of the feed direction which results in a higher cutting force. However, in down-milling, the cutting rotation is in the same direction as the feed direction which results in a lower magnitude of the cutting forces.

In the zig-zag tool path strategy, the tool engagement changes alternately from 180° in the horizontal direction to 120° for vertical direction. Based on the graph in Figure 7, there are significant changes to the cutting force when the zig-zag tool path strategy was used. The changes occur when the

tool turns its direction. As in the contour tool path strategy, the tool experiences both up milling and down milling throughout the path. For cutting temperature, it is noted that a higher cutting temperature occurs along L4 and L8 where there is full engagement between the cutting tool and workpiece. Before entering these paths, the cutting tool experiences up milling. This generates a large amount of heat at the cutting tool flank and workpiece resulting in higher cutting temperature [9]. At the end of the process, the cutting force is more stable. This is because after a certain period of time, the cutting parameters as well as other factors affecting the machining process become more significant compared to tool engagement.

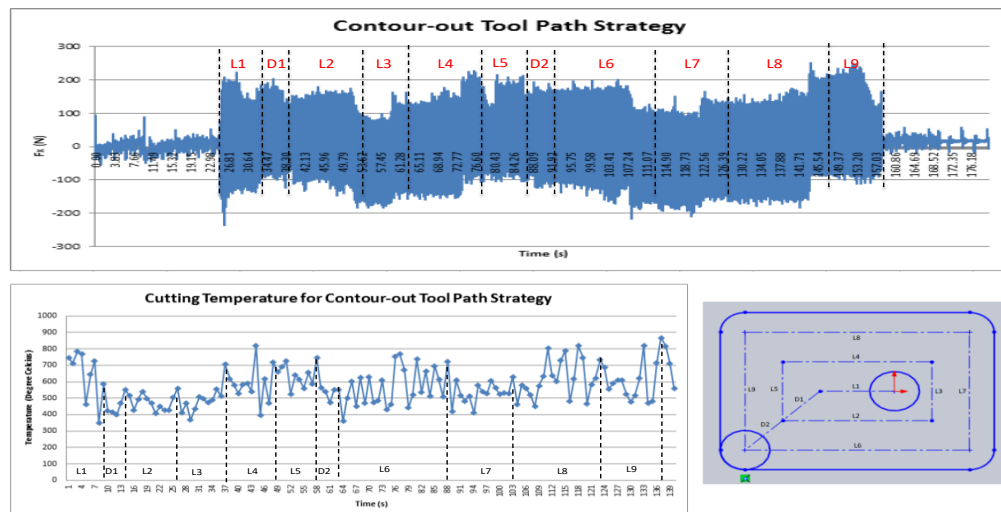


Figure 6. Cutting force and cutting temperature for contour tool path strategy

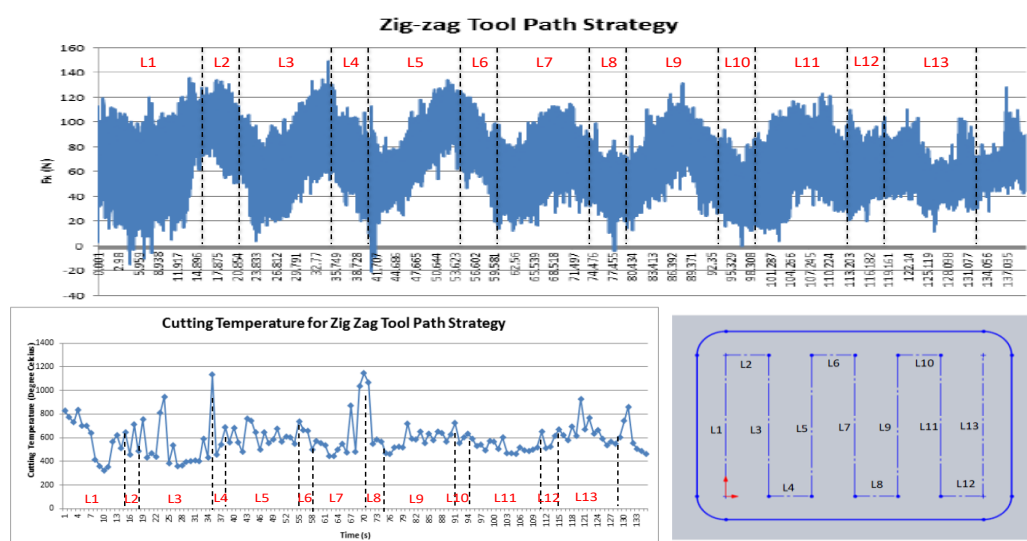


Figure 7. Cutting force and cutting temperature for zig-zag tool path strategy

4. Conclusion

The investigation of tool engagement in machining a pocket is very important. This paper reports on the cutting force and cutting temperature performances for different tool engagements. The findings from this study are as follows:

- i. The variations of tool engagement occur every time the cutting tool changes its directions. These variations affect the performance of cutting force and cutting temperature.
- ii. When applying the tool path strategies, the tool experiences up milling and down milling when the chip thickness is varied. A higher cutting force and cutting temperature is obtained when the cutting tool goes through up milling and when the cutting tool makes a full engagement with the workpiece.

This study can be improved by performing a detailed analysis of tool engagement and chip thickness for the different tool path strategies.

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