



## THE EFFECT OF TOOL PATH STRATEGIES ON CUTTING TEMPERATURE AND CUTTING FORCE DURING POCKET MILLING OF AISI H13

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### ABSTRACT

Cutting temperature and cutting force generated during high speed machining operations has been recognized as major factors influence tool performance and workpiece geometry. This paper aims to investigate cutting temperature and cutting force behaviours when contour-in and zigzag tool path strategies applied in high speed end milling process. The experiments were carried out on CNC vertical machining center by involving PVD coated carbide inserts. Cutting speed, feed rate and depth of cut were set to vary. Results obtained indicate that cutting temperatures and cutting forces are high in the initial stage of milling and at the corners region or turning points region. Portion of radial depth of cut with workpiece in combination with the abrupt change of the milling path direction occur particularly in acute internal corners of a pocket leads to rise of cutting temperature and cutting force.

**Keywords:** tool path, cutting temperature, cutting force, radial depth of cut, engagement angle.

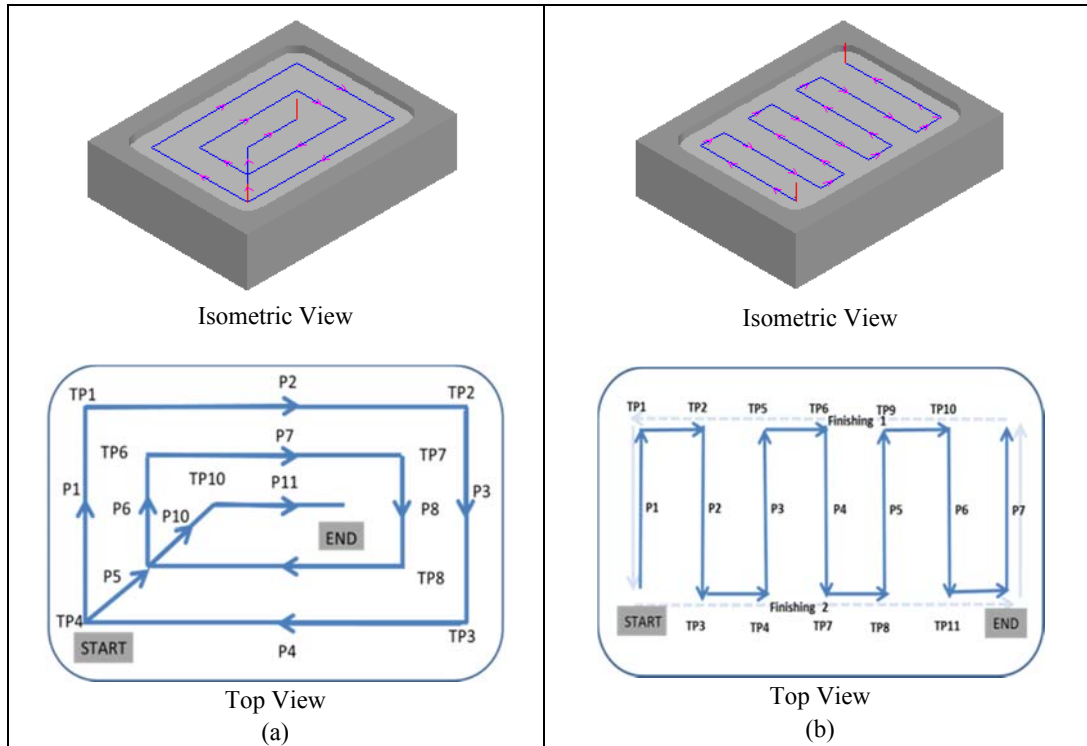
### INTRODUCTION

End milling is a widespread used machining process comprehensively in the manufacturing industry to remove layer by layer the material from the workpiece during milling process. Such process has been carried out to produce precision flat surface of mold and die and other components commonly used in industry. In milling process, machining parameters play the vital role to ensure the surface quality is needed meet the specification determined by the consumer. Besides the machining parameters such as cutting speed, feed speed and depth of cut, the selection of tool path strategy is considered as a critical stage in order to achieve the higher surface finish of mold and die. Many researches have been carried out to investigate cutting temperature during machining process specifically in milling operation. However, research related to tool path application and cutting temperature during milling operation have not yet established.

### RELATED WORK

Tool path is taken into account in milling operation due to its important role. Tool path has influenced on cutting force, vibration analysis, tool life, cutting temperature and workpiece surface integrity. Entirely, the influenced factors mentioned cause catastrophic failure of cutting tool [1]. The heat generated in cutting process is one of the most important issues in the metalworking industry. High temperature in metal cutting degrades the tool life, surface integrity, size

accuracy and machining efficiency dramatically [2]. There are two tool path strategies commonly used in pocket milling that are contour-in and zigzag strategy as seen in Figures 1 (a) and (b). The contour-in path is generated by successive offsets of the input profile. Thus, each successive offset is essential to generate a contour parallel tool path [3]. Zigzag strategy, also known as raster milling, staircase, sweep, hatch or lacing is a strategy where the cutting tool moves forward and backward linearly to the workpiece in the X-Y plane. Such cutting tool movement is defined differently by some researchers as up and down milling [1, 4]. On the other hand, such movement is defined by another researcher as switchbacks movements [5]. The advantage of using this strategy is short machining time and simple NC programming [6]. Among four tool path strategies studied that are spiral, radial, 3D-offset and raster, radial strategy provides the best results. This strategy produces the lowest cutting force, the best surface finish. The drawback of this strategy is the machining time spent is longer than other strategies [7]. The new cutting strategy by using a pivot point was used as entry strategy for cutting tool to cut material during peripheral milling. The pivot point applied leads to cutting tool enters the cutting area gradually until cutting tool is fully engaged with the workpiece. The smallest chip thickness produced is achieved when cutting tool exit the cut. As a result, cutting conditions and cutting force are lower compare to the conventional machining strategy [8].



**Figure-1.** (a) Contour-in strategy and (b) Zigzag strategy.

### EXPERIMENTAL SETUP

The experiments were conducted on CNC vertical machining center in dry cutting condition. PVD coated carbide insert and a 20 mm tool holder to cut AISI H13 workpiece material were used. This research adapted contour-in and zigzag tool path strategy. Response Surface Method (RSM) with a standard called Central Composite Design (CCD) has been employed to conduct 20 trials milling experiments. Metal cutting was performed at

cutting speeds 150, 200 and 250 m/min. with feed rate were 0.05, 0.10 and 0.15 mm/tooth. Depths of cut involved were 0.10, 0.15 and 0.20 mm for every cutting process. Thermal camera and dynamometer were used to measure cutting temperature and cutting force, respectively. Figure-2(a) shows experimental setup. Cutting temperature measured in this research was a cutting area between cutting tool and workpiece as seen in Figure-2(b).

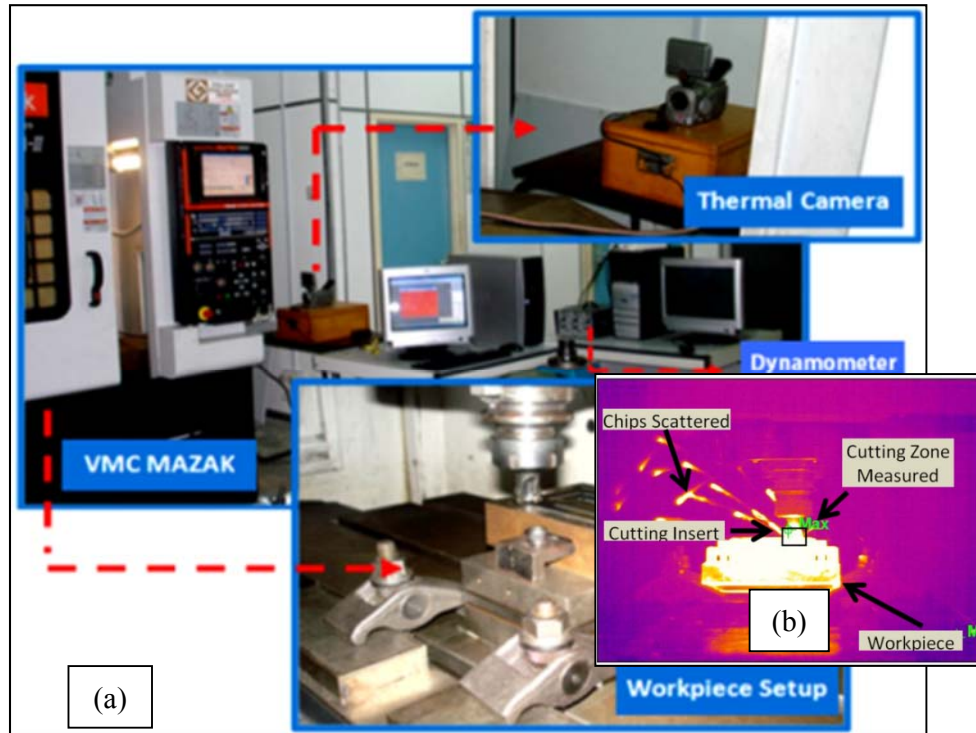


Figure-2. (a) Experimental setup; (b) Cutting zone.

## RESULT AND DISCUSSIONS

### Tool length and cutting time

Experimental results reveal that the number of paths including the finishing cut in order to make pocket for Contour-in and Zigzag tool paths are 11 and 13, respectively. The length of each tool path segments within a series of path can be calculated by summing up the length of each tool path segments that used to cut a pocket completely. Between two tool path strategies observed, zigzag strategy has a longer path than contour-in strategy. The length of contour-in strategy is 522.4 mm while the length of zigzag strategy is 600 mm. It can be concluded that the length of zigzag strategy is 12.9% longer than contour-in strategy. Figure 3 summarized the length and number of path segments of two different tool path strategies investigated in this research.

In this study, the machining time was measured for each strategy in all experiments. Variation of cutting time is occurred under different tool path strategy as seen in Figure-4. It can be seen that by increasing feed rate, cutting time decreases with length cut regardless of cutting tool path strategies applied. On the other hand, inclined strategy shows higher cutting time and length cut in

comparison to the other strategies. The results are consistent with research that has been carried out by previous researches [7, 9]. Furthermore, compared to zigzag strategy, machining time could be reduced by employing contour-in strategy at about 22.6%. Hence, the cutting time is the principle criterion which is important in order to decide the optimal strategy and cutting parameters.

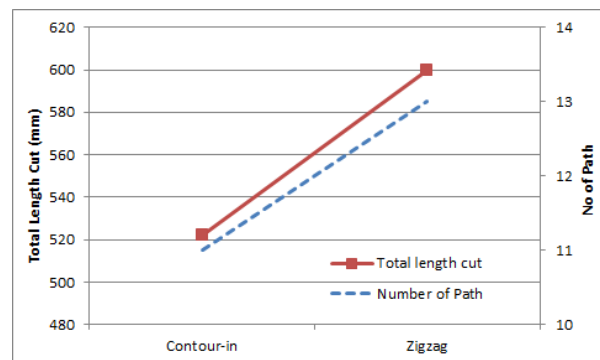


Figure-3. The length of path vs number of tool path.

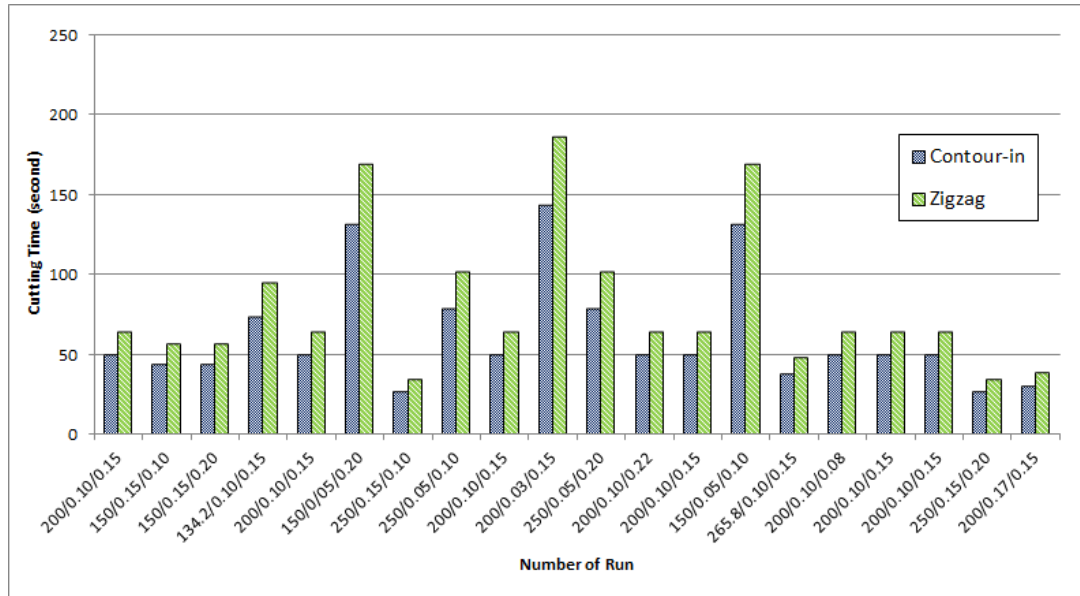


Figure-4. Cutting times with different tool path strategies and cutting parameters.

#### Tool path behaviours during pocket milling

Contour-in tool and zigzag tool path strategy which was used to create pocket shape during milling process is comprised to several stages. The variation of stage during pocket milling is based on tool movement to construct the path desired. Experiment proved that the pocket milling made by employing contour-in strategy is

much simpler compared to zigzag strategy. Therefore, contour-in and zigzag strategy is constructed by three and four stages, respectively. Each stage has its own characteristics. Figure-5 and Figure-6 show the tool path behaviours during pocket milling by employing contour-in and zigzag strategy with cutting speed of 200 m/min, feed of 0.10 mm/tooth and depth of cut of 0.15 mm.

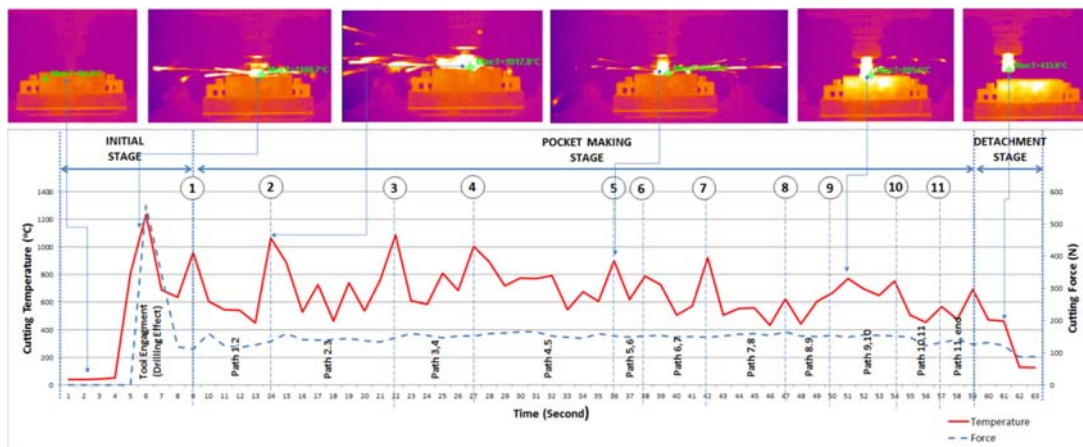
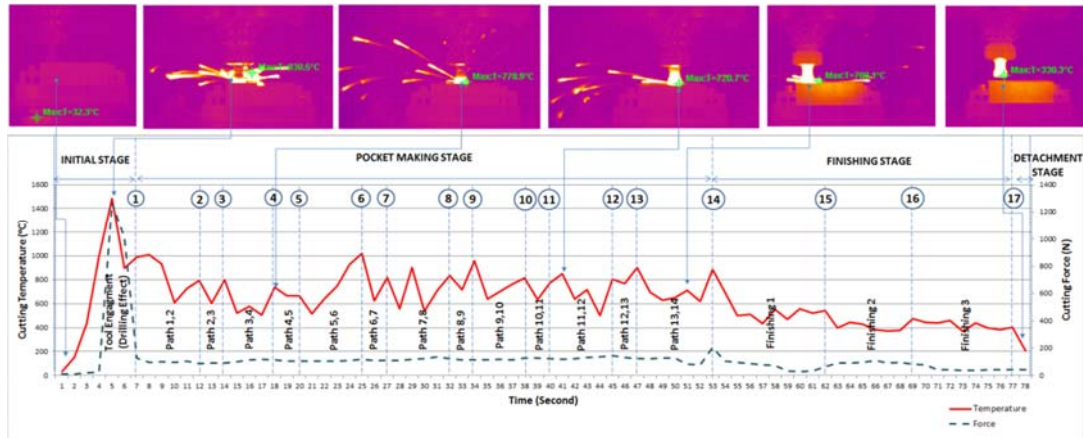


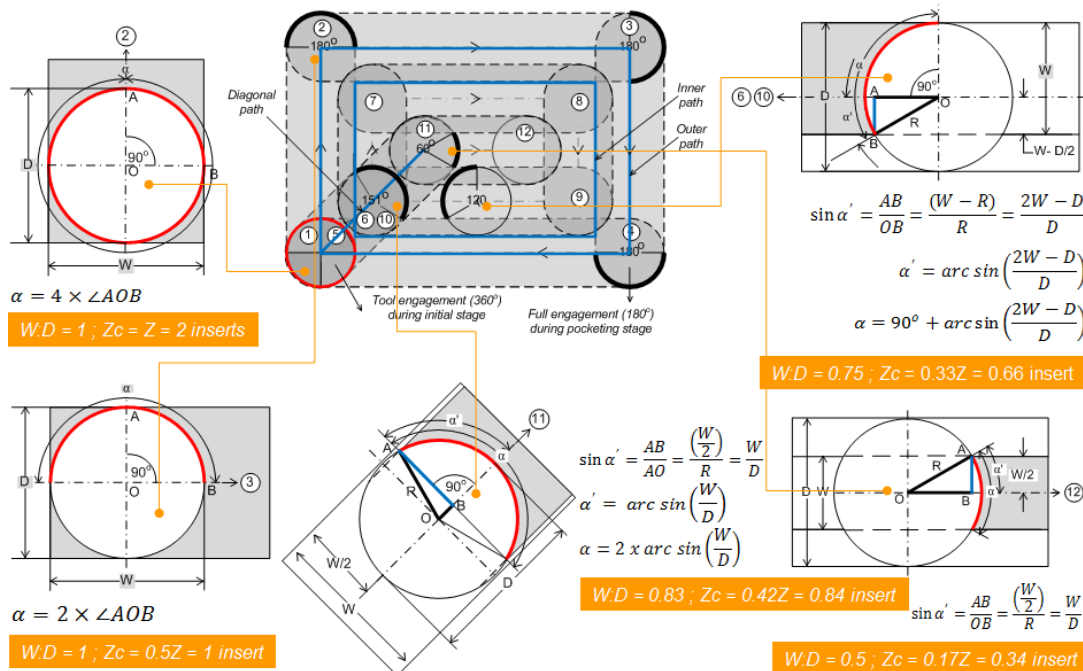
Figure-5. Tool path behaviours during pocket milling under contour-in strategy.



**Figure-6.** Tool path behaviours during pocket milling under zigzag strategy.

In the initial stage of machining process, cutting temperature and cutting force increases drastically in both strategies. This is due to cutting tool was fully engaged with the workpiece for the first time to achieve certain depth of cut desired perpendicularly. In this case, radial depth of cut plays an important role in order to increase the cutting force and cutting temperature. The movement of the cutting tool perpendicular to the work piece resulting in overall circumference of the cutting tool

engaged with the workpiece. When the radial depth of cut of cutting tool increases, time-in cut-per-tooth required become longer and contact area between cutting tool and workpiece is increased. The workpiece and heat generation is then localized in a small area which produces high cutting force. As consequences, the cutting temperature increases during this initial stage. Figure-7 shows the model of tool engagement angle and its position in pocket milling.



**Figure-7.** Map of tool engagement angle during pocket milling process.

In the pocket making stage, cutting temperature and cutting force is recorded high at the corner regions and turning points on both strategies employed. Beside the radial depth of cut which causes high cutting force, the

length of time is required by cutting tool in the specified corner region is also effect to cutting temperature increases. It is due to when the cutting tool reaches the corner region of pocket with sharp corner, the spindle has



to decelerate the feed speed and cutting speed in order to allow the cutting tool change its direction. The spindle then accelerates the feed rate and cutting speed again until the desired machining parameters are reached. The moment when the acceleration and deceleration occurred at a corner region provide long time for the cutting tool and the workpiece engage. It also gives enough time for cutting tool and workpiece to produce heat. This movement does not only provide the time for cutting tool and workpiece to produce heat but also produce force when cutting tool is accelerated.

The only stage that contrasted between contour-in and zigzag strategy is that zigzag strategy has a finishing stage. The finishing stage is the movement of cutting tool removes an outer material which has not been covered from the pocket making stage. Since the small amount of work materials removed from the workpiece and the small portion of radial depth of cut engaged with, it impacts on the reduction of cutting temperature and cutting force. This stage is considered as one reason the tool path length of zigzag is longer than contour-in. As result, the cutting

time is longer than expected. The last stage is called the detachment stage. In the tool detachment stage cutting temperature was recorded to decrease gradually. It is occurred when cutting tool move away from the workpiece. The heat produced from friction between cutting tool and workpiece gradually dissipated through the spindle rotation. This stage is not so much effect to cutting force and cutting temperature.

### Cutting force

Based on the results, Figure 8 compares the cutting force components obtained when applying various tool path strategies. It is observed that when milling with zigzag strategy, the highest resultant cutting force is observed followed contour-in strategy. Since the comparison between strategies takes place in similar machining conditions, cutting tool engagement is one of the reasons for cutting force differences between different strategies.

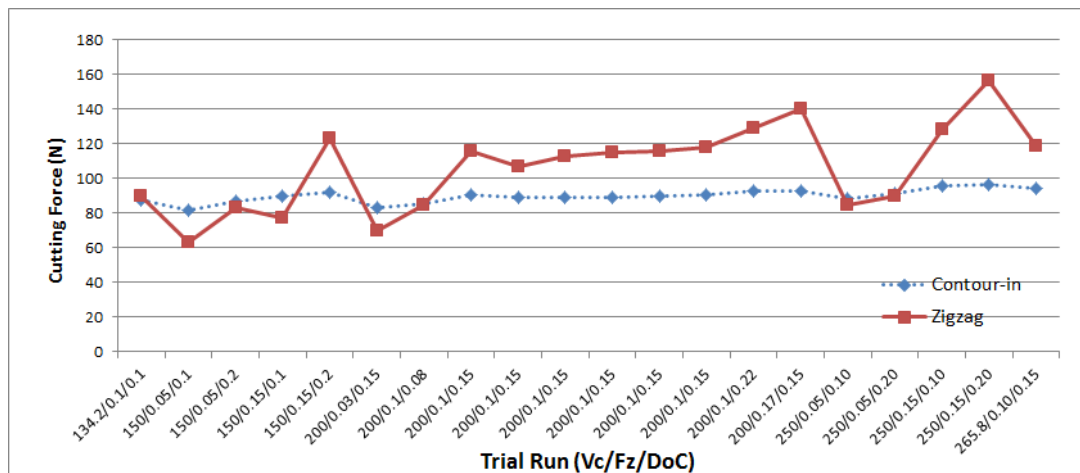


Figure-8. Comparison of tool path strategies for cutting force.

In end milling of pocket, the engagement angle between cutting tool and workpiece differs significantly when employing different tool path strategies. Radial depth of cut is one of the factors that affect cutting tool engagement. Radial depth of cut depends on the tool diameter and tool path strategy employed during end milling. Radial depths of cut formed leads to tool engagement angles were varied when cutting tool moves along the cutting area. Tool engagement formed can be seen in Figure-9.

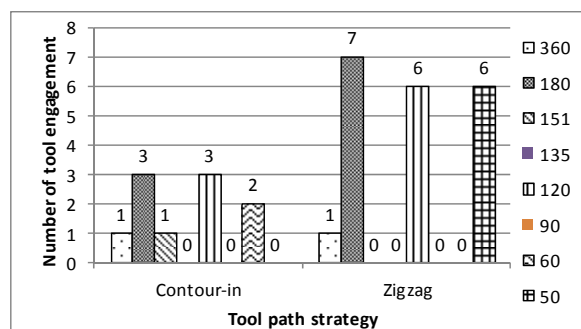


Figure-9. Number of tool engagement for different tool path strategies.

It can be seen that when milling with zigzag tool path strategy, the highest cutting force is observed



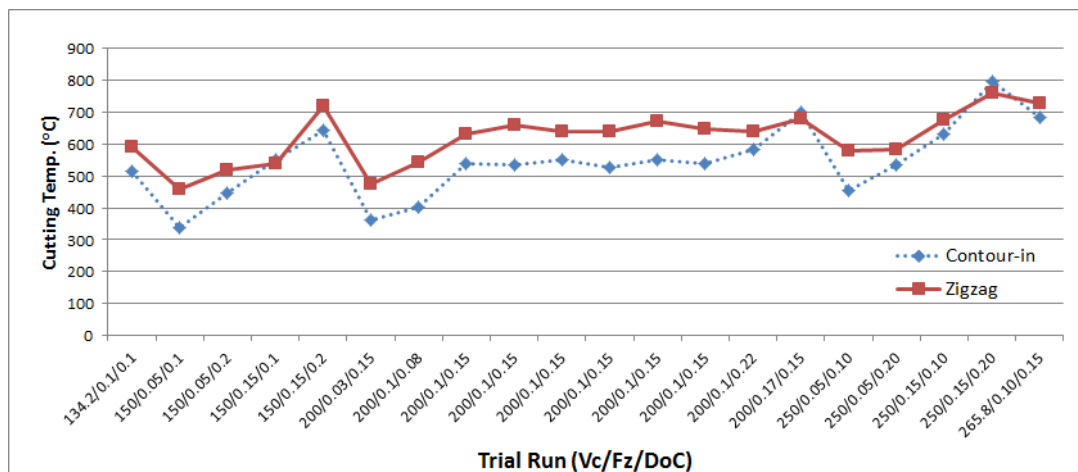
followed contour-in strategy. High value of cutting forces occurred in inclined tool path strategy because most of tool engagement formed is dominated by large tool engagements angle. There are 14 locations of tool engagement angle formed during end milling having engagement angle greater than 90° which is categorized as large tool engagement angle. Meanwhile contour-in strategy only has 7 locations. Therefore, the larger radial depth of cut, the larger tool engaged with the workpiece, the larger cutting force is expected. According to current research, it is shown that tool engagement in inclined strategy is the largest and in contour-in strategy is the smallest amount. Thus, cutting force is the most for inclined strategy and is the least for contour-in strategy.

Tool path design also affects the number of turning points that formed in a pocket. The movement of the cutting tool in making the pocket results in the amount of turning points and patterns are varied for each tool path strategies are used. Turning points is the location in the pocket where the directions of cutting tools are changed. Problems due to large radial depth of cut and rapid exchange of cutting direction at the turning point and

corner regions will result in high cutting force. The results of cutting force measurements in average obtained from the research for each strategy include contour-in is 78.86 N and zigzag is 102.35 N.

### Cutting temperature

Figure-10 shows the results all experiments by comparing the cutting temperatures measured for various tool path strategies. It is observed that when contour-in tool path strategy used in milling of pocket, the lowest cutting temperature is recorded. However, the highest cutting temperature is observed when milling with zigzag strategy. Results of cutting temperature measurements in average for contour-in and zigzag tool path strategy are 534.7 °C and 623.2 °C, respectively. It is obviously can be seen that contour-in is the tool path strategy which produce the lowest cutting temperature among tool path strategies tested. Such conditions are caused by abrupt changes and tool engagement employ during milling operation.



**Figure-10.** Comparison of tool path strategies for cutting temperature.

Abrupt change of cutting tool direction occurs at the corner regions and turning points where the cutting tools change its direction. When cutting tool enter and exit the corner regions or turning points, the high impact forces are produced. Moreover, maximum tool engagement employ at the corner region make the radial length of cutting tool involved larger. The larger radial length of cutting tool involved the higher friction at the cutting edge. As a result, the chip volume increases which produce high friction at the cutting edge and increases cutting temperature. As seen in Figure-9, number of turning points and number of large tool engagement is dominated by inclined and zigzag strategy. Therefore, cutting temperature for both strategies are higher than contour-in strategy. The combination abrupt change of

cutting tool direction and large tool engagement are claimed as the main factors rise of cutting temperature.

### CONCLUSIONS

In this paper, effect of tool path contour-in and zigzag tool path strategy on cutting temperature and cutting force during pocketing were investigated. The essential conclusions can be drawn are as follows:

1. Contour-in has a simple path when compared to zigzag strategy. The direct effect of this simple path is reduced of cutting time. By simplifying the tool path, the number of turning points and corner regions can be reduced. In turn, the effect of them such as high cutting temperature and excessive cutting force can be eliminated.



2. Initial stage produces the cutting force and cutting temperature is higher than other stages in all strategies. This is due to cutting tool was fully engaged (100 % engagement) with the workpiece when the cutting tool for the first time is engaged with the workpiece to achieve certain depth of cut desired perpendicularly. Meanwhile the detachment stage produces the lowest cutting force and cutting temperature. This is because in this stage only small force needed to remove the material which is not covered by previous stages.
3. Tool engagement angle and radial depth of cut are two factors affect to insert engaged during pocket milling process. Contour-in tool path strategy was claimed as the tool path which has radial depth of cut sizes is smaller on average, while the inclined strategy is the one with the average radial depth of cut bigger. The bigger radial depth of cut (combined with the effect of turning points) the higher cutting force and cutting temperature is produced.

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