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PREDICTIVE MODELLING OF CUTTING FORCE IN POCKET MILLING OF HARD-TO-CUT MATERIAL

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Abstract

The experimental study was performed on CNC vertical machining center Mazak Nexus 410A-II CNC Mill in the absence of cutting fluid application. The experiments adopted contour-in tool path strategy for pocket millings machining by varying the cutting parameters. A total of 20 runs designed with Design of Experiment software were tested. It was observed that inclined strategy exhibits a higher cutting force, and subsequently followed by zigzag and contour-in strategy. The high value of cutting forces occurred in the inclined tool path strategy was mostly due to the large tool engagements angle dominating most of the tool engagement forms. In this research, empirical model of cutting force for contour-in strategy is developed.

Keywords: Tool Path; AISI H13; Cutting Force; High Speed End-Milling.

1. INTRODUCTION

Cutting forces are the primary factors regulating machining accuracy, surface finish, tool wear and cutting temperature. The merit gained in alleviating cutting force may include the improvement of surface roughness yet extending the life of the cutting tools and consequently reducing the machining costs. For this particular reason, the analysis on the different tool path strategies application for AISI H13 pocket milling were made through a comparison of cutting force measurements. Cutting forces increase with the increase of feed rate, while cutting temperature increases with the increase of cutting speed [1]. The effects of cutting speed on cutting forces and feed rate on cutting temperature are not significant. The cutting parameters effect in various speed ranges towards the cutting force. The cutting parameters of cutting speed, feed per tooth, and axial depth of cut influence the resultant cutting force [2]. The total machining force is defined through the resultant cutting force (as Ftotal). In a consecutive way, the highest resultant cutting force in a milling process was attained by spiral strategy, followed by 3D-offset, raster and radial strategies [3]. As the cutting speed increases over 800 m/min, the influence of feed per tooth and axial depth of cut on resultant cutting force increases and decreases, respectively. The tool wear affects cutting force more significantly compared to the cutting temperature. At the cutting speed of 800 m/min is a critical value that can produce low mechanical load, relatively low degree of chip segmentation, and relatively long tool life can be obtained at the same time. Cutting forces and the degree of chip segmentation increase with the cutting speed. The plastic deformation that develops at the shear angle prompts the increase of cutting force as the cutting speed elevates [4].

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There is also a positive correlation between the cutting feed and the cutting force. This is due to the higher amount of energy required for the material removal process. The higher cutting force is observed as the amount of materials to be cut increases [5],[6]. The cutting speed of 1400 m/min can be considered as a critical value for both the average value of the resultant cutting force and tool life [7]. The cutting forces and cutting temperatures increase by increasing the hardness of the AISI H13 [8]. Many researches have been carried out to investigate cutting force during machining process in milling operation. However, research related to tool path application and cutting force during milling operation have not yet established. In addition to that, this research is valuable for the die and mould maker to select proper cutting condition to avoid increase in cutting force.

2. METHODS AND MATERIALS

The current work used 48HRc hardened and tempered H13 steel block as the workpiece material, with the size of 130×100×30mm. The pocketing process employed a cutting tool with a diameter of 20 mm that accommodates 2 indexable inserts in each cutting process. Coated carbide mill inserts of CoroMill 490 were utilized with cutting speed, feed rate and depth of cut as the cutting parameters. CoroMill 490 accomodates four-edge inserts in which for every different cutting parameter, only one cutting edge is applied. The new cutting edge was then utilized for the cutting process of the pocket feature, where the insert tools were securely fastened to the tool holder. The cutting force measurement involved a dynamometer along with its charge amplifier, signal analyzer and signal conditioner to measure the cutting force. Fig. 1 shows the details of the experimental setup.

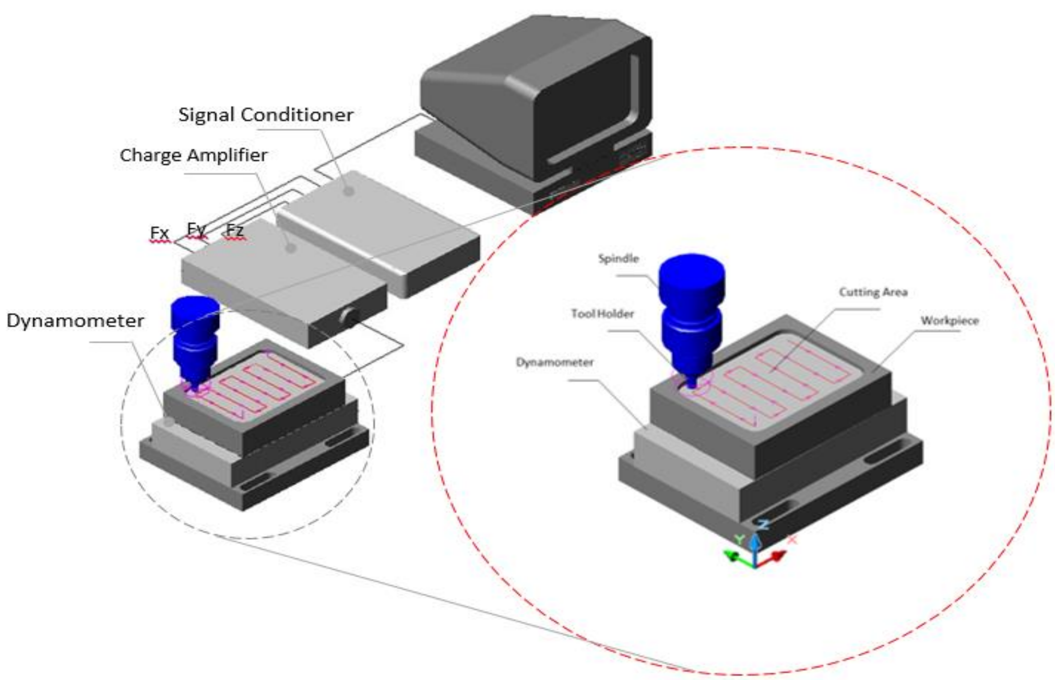

Fig 1: Schematic diagram of experimental setup

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3. RESULTS AND DISCUSSION

3.1 Effect of Cutting Force on Tool path Strategies

Fig. 2 presents the results and correlates the cutting force components measured when different tool path strategies assigned. The highest cutting force found when milling with inclined strategy was applied, where contour-in and zigzag strategies followed after. Cutting tool engagement observed as one of the reasons for the variation in cutting forces when different strategies applied, as their comparison was conducted in similar machining conditions.

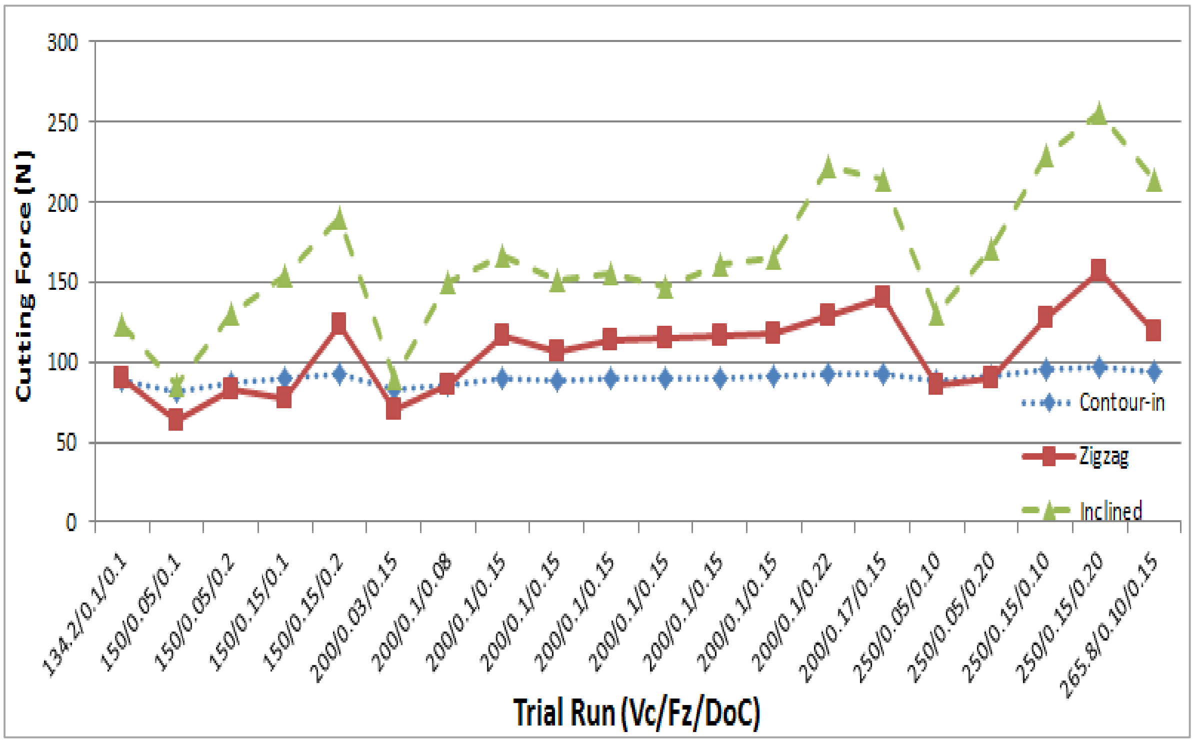

Fig 2: Comparisons of tool path strategies for cutting force

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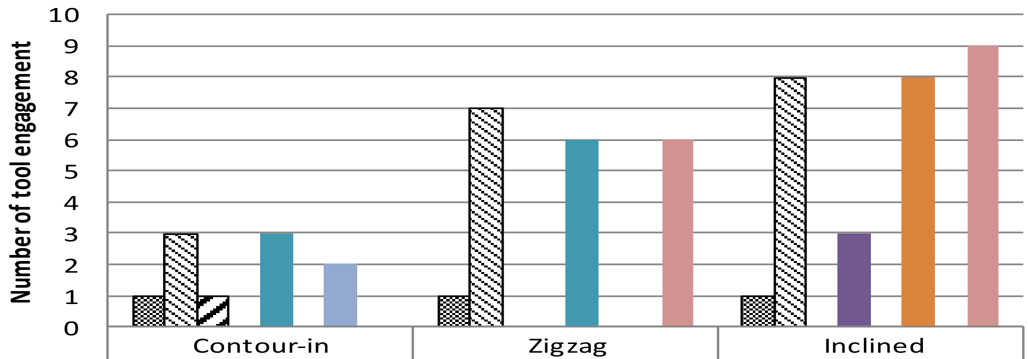

	Contour-in	Zigzag	Inclined
360	1	1	1
180	3	7	8
151	1	0	0
135	0	0	3
120	3	6	0
90	0	0	8
60	2	0	0
50	0	6	9

Fig 3: Different tool path strategies effect towards sizes of angle and number of tool engagement during end milling observation

A significant difference was detected at the end milling process of pocket where the engagement angle between workpiece and cutting tool was observed when different tool path strategies employed. One of the variables affecting the cutting tool engagement is the radial depth of cut. Meanwhile, the tool engagement angle was subjected to the tool path strategy selected during end milling. Fig. 3 represents the size and number of tool engagement formed in the process.

The inclined strategy was observed to give the highest cutting force, followed by zigzag and contour-in strategy. The domination of large tool engagement angle at the inclined tool path strategy led to the high value of cutting forces. A large tool engagement angle is defined when the angle itself is larger than 90˚, and there were 20 points of them observed at the inclined strategy during the end milling. The result showed a lower value for the contour-in and zigzag strategy at 7 and 14 points, respectively. Thus, as the radial depth of cut expands, the larger the tool engagement with the workpiece can be expected, which later leads to the larger resulting cutting force. Based on this study, the largest tool engagement observed was attained by the inclined strategy, and the smallest one was associated with the contour-in strategy. Consequently, the highest cutting force applied for the inclined strategy, while the opposite applied for the contour-in strategy.

The number of turning points was also affected by the tool path during pocket formation. Patterns were varied for each tool path strategies, and the cutting tool movement led to the difference in the number of turning points. Turning points can be defined as the point in the pocket area where cutting tools alter its direction. A high cutting force may emerge

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if there are problems caused by the rapid exchange of cutting direction and large engagement angle at the corner regions and turning points. In average, the cutting force measurements of the study show 78.86 N, 102.35 N and 163.30 N for contour-in, zigzag and inclined strategies, respectively. The investigation showed that a lower cutting force of 46% and 36% were produced by contour-in and zigzag strategy when they are compared to the inclined strategy.

4.2 Cutting Force Modeling

The experimental results were explained through the investigations, calculations and explanation of the empirical model. It was a representative of real machining process through a complex small-scale machining process. The correlation between the decision variables parameter (cutting speed, depth of cut and feed per tooth) and the responses parameter (cutting force) represent the machining process models of the study.

The following study exclusively modelled the contour-in tool path strategy which produced the lowest cutting force detected. A pocket milling operation with contour-in tool path strategy and three variables of cutting speed, feed per tooth and depth of cut was performed towards AISI H13 tool steel. Table 1 shows the machining parameters and conditions details applied in the study.

Table 1: Machining condition for response output

Tool path strategy	Machining parameter		
	Cutting speed (m/min)	Feed per tooth	Depth of cut
Contour-in	150 < x < 250	0.05 < x < 0.15	0.10 < x < 0.20

The empirical model employed in the study was central composite design (CCD) of response surface method (RSM). According to the model, twenty runs of experiments should be applied. Table 2 presents the collected data of output response under contour-in strategy and the input parameter values that corresponded to the CCD design.

Table 2: Data of machining parameters and responses for contour-in tool path strategy

Run	Point's location	Input Variables						Cutting Force (N)
		Coded form			Real value			
		X_1	X_2	X_3	Vc (m/min)	Fz (mm/tooth)	DoC (mm)	
1	Factorial	-1.00	1.00	-1.00	150.00	0.15	0.10	89.6
2	Centre	0.00	0.00	0.00	200.00	0.10	0.15	90.4
3	Factorial	1.00	-1.00	-1.00	250.00	0.05	0.10	88.0
4	Factorial	-1.00	-1.00	1.00	150.00	0.05	0.20	87.2
5	Axial	1.32	0.00	0.00	265.80	0.10	0.15	94.4
6	Factorial	1.00	1.00	-1.00	250.00	0.15	0.10	96.0
7	Axial	0.00	1.32	0.00	200.00	0.17	0.15	92.8
8	Centre	0.00	0.00	0.00	200.00	0.10	0.15	88.8
9	Centre	0.00	0.00	0.00	200.00	0.10	0.15	89.3
10	Axial	0.00	-1.32	0.00	200.00	0.03	0.15	83.2
11	Axial	0.00	0.00	-1.32	200.00	0.10	0.08	85.6
12	Axial	-1.32	0.00	0.00	134.20	0.10	0.15	87.8

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13	Factorial	1.00	1.00	1.00	250.00	0.15	0.20	96.8
14	Centre	0.00	0.00	0.00	200.00	0.10	0.15	89.1
15	Factorial	-1.00	-1.00	-1.00	150.00	0.05	0.10	81.6
16	Factorial	1.00	-1.00	1.00	250.00	0.05	0.20	91.2
17	Axial	0.00	0.00	1.32	200.00	0.10	0.22	92.8
18	Centre	0.00	0.00	0.00	200.00	0.10	0.15	90.1
19	Centre	0.00	0.00	0.00	200.00	0.10	0.15	90.8
20	Factorial	-1.00	1.00	1.00	150.00	0.15	0.20	92.0

The ANOVA model for Cutting force model resulted from the contour-in strategy can be identified from Table 3. The model is suggested to be significant with the probability of F < 0.0001 and the "Prob > F" values to be less than 0.0500. With an F-value of 52.35, there is only 0.01% of chance that the F-Model is wrong due to noise. The significant cutting force model terms for the contour-in strategy are all the main effect, two level interaction between feed per tooth and depth of cut (BC), as well as second order of cutting speed (A2) and feed rate (B2). However, the cutting force was significantly influenced by feed per tooth at the F-value of 155.95 when the contour-in strategy applied. Cutting forces were noticed to be highly influenced by feed rate rather than the cutting speed and depth of cut.

The model is sufficient with insignificant Lack of Fit test result at 32.37% relative to the pure error. The R2 is relatively high and near to 1 with value at 0.9419. Furthermore, the R2predicted of 0.9011 is in reasonable agreement with the R2adj of 0.9419. The adequate precision value for the model is 28.985, and it is greater than the desirable criteria of 4. The second order of feed per tooth (B2) was also found to be significant in the application of contour-in strategy.

Table 3: ANOVA model for cutting force model under contour-in strategy

Source	**Sum of Squares**	**df**	**Mean Square**	**F-Value**	**p-value Prob > F**	**Significance**
Model	267.71	6	44.62	52.35	< 0.0001	significant
A-Cutting Speed	79.73	1	79.73	93.55	< 0.0001	
B-Feed per Tooth	132.91	1	132.91	155.94	< 0.0001	
C-DOC	40.23	1	40.23	47.20	< 0.0001	
BC	3.92	1	3.92	4.60	0.0515	
A2	9.61	1	9.61	11.27	0.0052	
B2	2.95	1	2.95	3.47	0.0854	
Residual	11.08	13	0.85			
Lack of Fit	7.91	8	0.99	1.56	0.3237	not significant
Pure Error	3.17	5	0.63			
Cor Total	278.79	19				
R2 = 0.9603	Adj. R2 = 0.9419		Pred. R2 = 0.9011		Adeq. Precision = 28.985	

The normality of residuals was evaluated by the normal probability plot of the studentized residuals and is presented on Fig. 4. The plot shows that the errors are distributed normally which is inferred by the points on the plot that lie reasonably close to the straight line. This can lead to a conclusion that the underlying assumptions of the analysis are satisfied, as the cutting speed (A), feed rate (B) and depth of cut (C) are found to be

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significant. On the other hand, Fig. 5 helps to explain the check for constant error via the plot of the studentized residuals versus predicted values. It was observed that there is no unusual structure or obvious pattern exposed from the plot. Thus, it is concluded that the model proposed are adequate.

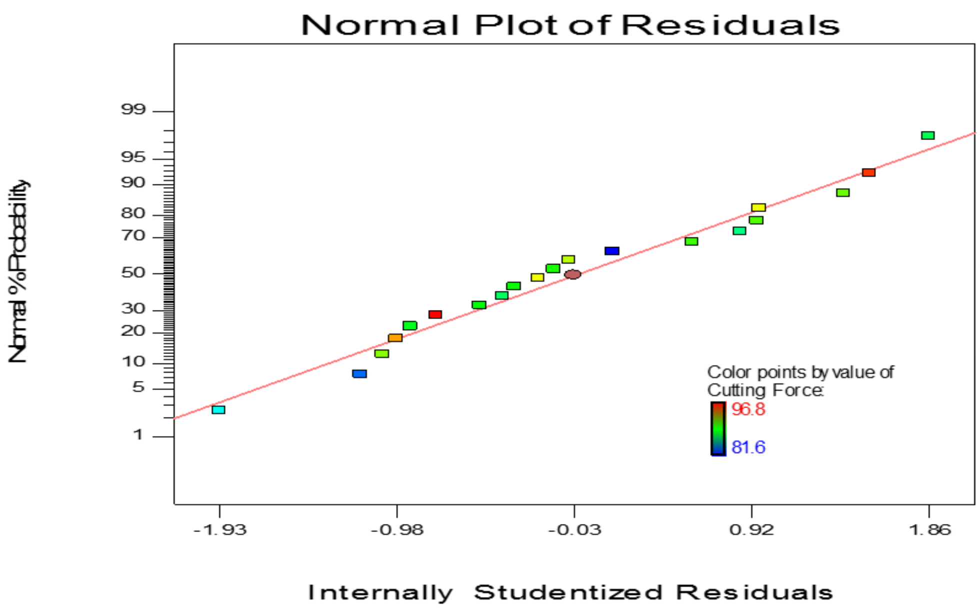

Fig 4: Cutting force normal probability of residuals for data under contour-in strategy

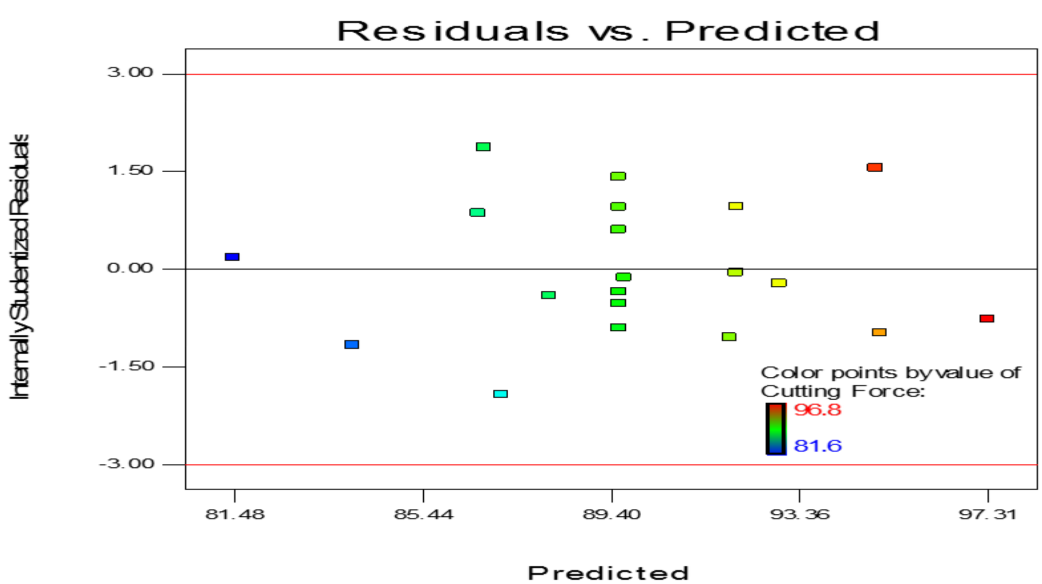

Fig 5: Cutting force plot of residuals vs. predicted response for data under contour-in strategy

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The coded form for the effect of input parameters was generated by Design Expert software in a perturbation plot at Fig. 6. From the figure, the quadratic comparable effect of the cutting forces can be seen observed from the three input parameters of cutting speed, (A), feed rate, (B) and depth of cut (C). The feed per tooth factor was considered to be the most influential factor for the cutting force. The figure also presented that the cutting force is lower when cutting parameters with lower input were applied, compared to the higher cutting range. The cutting force was also less affected at lower range (-1) feed rate. The reason was the decreasing chip thickness when the feed per tooth was low, Due to the combined effects of feed rate and radial depth of cut. Following the decreasing chip thickness, the requirement for the cutting force and energy to cut the material from the workpiece is also decreased. Thus, the lower feed per tooth leads to the lower cutting force.

The cutting speed factor leads to higher cutting force at the higher machining range, compare to feed per tooth and depth of cut. In the orderly manner, the cutting force was produced at the highest by being affected to the cutting speed, feed per tooth, and depth of cut, respectively. The explanation was predicted to the time when cutting speed adopted was high, thus the revolutions per second increased accordingly. Consequently, the engagement time between the workpiece and the cutting insert were increased. This led to the increase of the heat at the workpiece and cutting insert engagement area. The heat was generated by the corresponding condition, causing the cutting insert to wear rapidly. It was observed that the higher rate of tool wear has a greater influence on cutting forces. Nevertheless, the dominance was still observed at the combination of depth of cut and feed per tooth when the aim is the cutting force minimization during machining.

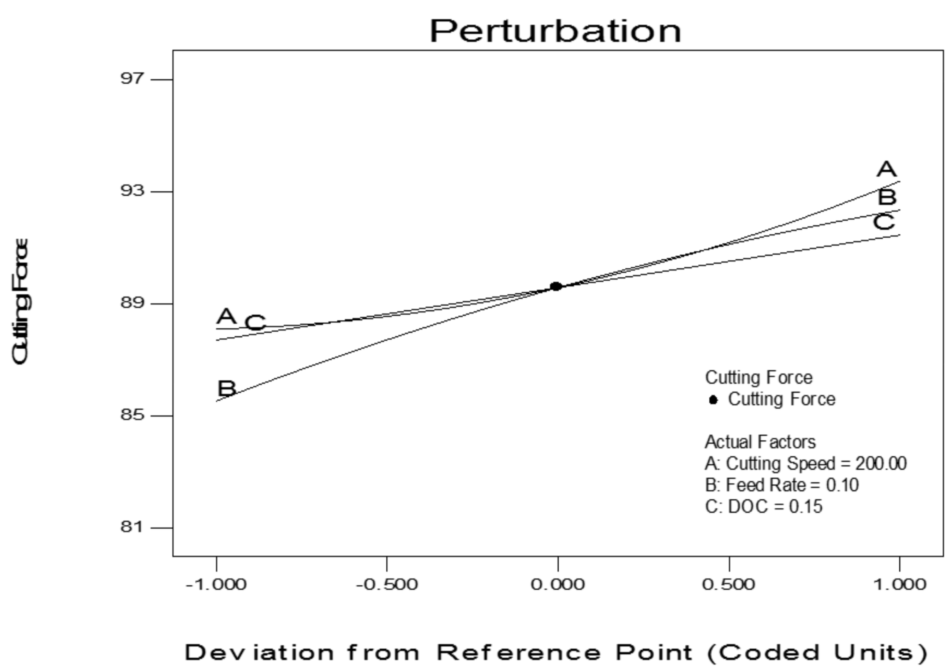

Fig 6: Cutting force perturbation plot with contour-in strategy applied

(Vc = 200 m/min, Fz = 0.10 mm/tooth and DoC = 0.15 mm)

Fig. 7 shows the three-dimensional graph for cutting force when contour-in strategy was applied. The graph model is quadratic-fitted with curvilinear profile. It was observed that the cutting force was increased as the cutting speed raised from 150 m/min to 250 m/min. A similar trend was also observed for feed rate. Based on the result, it was evident that for lower cutting force to be acquired, the machining parameters supposed to be set to the lower cutting speed and feed per tooth.

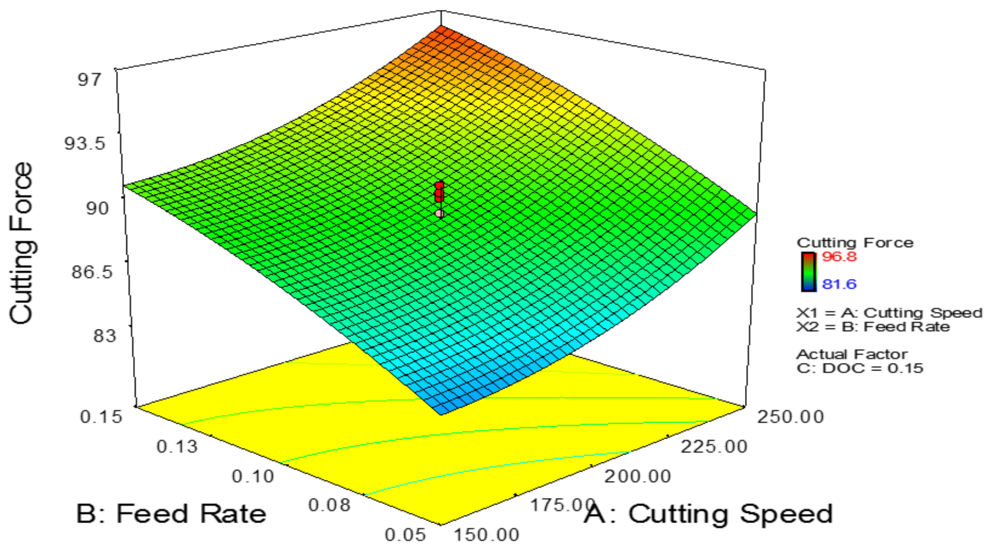

Figure 7: Predicted cutting force contour graph with the application of contour-in strategy

Equation (1) describes the cutting force model for the response variables during the application of contour-in strategy.

Fcont. = 89.58 + 2.64 *A + 3.40 * B + 1.87 * C - 0.70 * B * C + 1.16 * A2 - 0.64* B2

The equation illustrates the quadratic surfaces depicted at Figure 4.44. The graph curvature appeared due to the quadratic term in the direction of A2 and B2. The cutting force was observed to be low at the lower application of cutting speed and feed per tooth, then moved quadratically higher as cutting speed and feed per tooth went to the higher range of machining parameters. The upward trend of cutting speed (A) is indicated by the positive (+) sign, while the negative (-) sign signifies the feed per tooth (B) for a downward trend. The surface in Fig. 7 also demonstrates that for one particular value of A, there is a pair unique value of B that magnifies the cutting force.

4. CONCLUSIONS

The major discoveries of this study are enlisted at the following concluding remarks:

1. Contour-in strategy was found as the tool path strategy with the lowest cutting force in contrast to zigzag and inclined.

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2. The domination of the large tool engagements angle in the inclined tool path strategy led to the high value of cutting forces.
3. The contour-in strategy analysis for cutting force revealed that the feed per tooth is the most influential factor, compared to cutting speed and depth of cut.

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