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Optimisation of Surface Roughness in The Cnc Milling Process

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Abstract: The main aspect for machining today is to produce and achieve a better surface quality in a short period and with a lower energy consumption. Surface roughness is a common criterion of the quality characteristics for machining processes. In order to increase the consistency of the surface finish, the suitable cutting parameters should be implemented. This thesis aimed to optimise the surface roughness in 3D cutting using CNC end milling machine. The depth of cut, the cutting speed and the feed rate are the parameters used in optimising the surface roughness. The best range of the cutting parameters was obtained by using Dthe esign of Experiment (DOE) which is Response Surface Methodology (RSM) method. The RSM method is used because it is one of the most efficient and effective techniques to determine the best combination of parameters. The experiments were run by using the data simulation from Mastercam X7 and all the data command were used in Nexus 410A-II 3-Axis Computer Numerical Method (CNC) machine with the MAZATROL controller. The surface roughness of workpiece is measured using surface roughness tester, Mitutoyo SJ-410. The analysing data are made by employing RSM and ANOVA using Minitab 19 software. The direct effects and interaction effects were graphically plotted which helps to study the significance of these parameters on surface roughness.

Keywords: Surface Roughness, Response Surface Methodology, Cutting Parameters, CNC End Milling Machine, Minitab 19 Software, Mastercam X7, ANOVA

1. Introduction

Machining quality is measured from the surface finish and in order to improve the surface quality, it is important to set appropriate and optimum machining parameters during machining work [3]. Efficient machining parameters play a very important role in manufacturing process to improve manufacturing efficiency and to cut down the cost in production [3]. There are different combinations of parameters such as cutting speed, feed rate and depth of cut. Depending on the machining target and tool selection, to achieve different results regarding machined surface quality and tool wear. Surface

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roughness has a major impact on dimensional accuracy, machine component performance, and manufacturing costs [4]. The difference in surface roughness and tool life depending on the combination of cutting parameters. The quality of the machined surface is evaluated by the surface roughness of the machined part, which is the most important quality characteristic [5].

Response surface methodology (RSM) is the most effective method to analyse the result obtained from factorial experiments. It is an effective tool for modelling and studying the manufacturing problems which in this project is about end milling cutting parameters. RSM has been used for roughness modelling and optimisation in CNC end milling. RSM takes on both mathematical and statistical techniques which are useful for the modelling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimise the response. In most of the RSM problems, the form of the relationship between the response and the independent variables is unknown. Thus, the first step in RSM is to find a suitable approximation for the true functional relationship between response of interest 'y' and a set of controllable variables $\{x_1, x_2 \ldots\ldots x_n\}$. Usually when the response function is not known or non-linear, a second-order model is utilised in the form of equation (1) shown below:

$$y = b_0 + \sum_{i=1}^{n} b_i x_i + \sum_{i=1}^{n} b_{ii} x_i^2 + \Sigma \sum_{i<j} b_{ij} x_i x_j + \varepsilon$$

where ε represents the noise or error observed in the response *y* such that the expected response is (*y*) and *b'*s are the regression coefficients to be estimated.

2. Methodology

Determine all the influential parameters that will give big effect towards surface roughness of the workpiece. Then, all the information will be put in the constructed design of experiment which is RSM in Minitab 19 software. We will get sets of parameters combination and all that data will be used to run the experiment. Simulation of milling process will be run in the Mastercam X7 software. The simulations need to be done at first to identify the best parameters for milling and the design of the workpiece for this experiment. After we run the simulation, the simulation data that have been created (commands) will be use to run the experiment through CNC end milling machine. The roughed surface of each workpiece will be measured using surface roughness tester, Mitutoyo SJ-410 to get the value of Ra, average surface roughness. All the data obtained will be analyse to find out the best set of parameters in minimizing the roughness of surface of workpiece. This data analysis will be performed under RSM method.

2.1 RSM Design

In this study, Box-Behnken design had been used to determine the factors level that simultaneously satisfy a set of desired specifications, to select the ideal combination of factors that yield a desired response and describes the response near the optimum, to determine how a specific response is affected by changes in the level of the factors over the specified levels of interest, and achieve a quantitative understanding of the system behaviour over the region tested. Cutting speed, cutting feed rate and depth of cut has been considered as the cutting parameters. 3 levels of each parameter will be used which is 3^3 factorial design. This design of experiment which is RSM will be run using Minitab 19 software.

Table 1: Parameters setting and levels

No	Factors	Levels		
		1	2	3
1	Cutting Speed (rpm)	960	1200	1440
2	Feed Rate (mm/min)	500	550	600
3	Depth of Cut (mm)	0.50	0.60	0.70

Table 2: Box-Behnken design

Run Order	p. type	Blocks	Parameters		
			Cutting speed (rpm)	**Feed rate (mm/min)**	**Depth of cut (mm)**
1	2	1	1200	500	0.5
2	0	1	1200	550	0.6
3	2	1	1200	500	0.7
4	2	1	960	550	0.5
5	2	1	1200	600	0.7
6	2	1	1440	550	0.7
7	2	1	960	600	0.6
8	2	1	1440	600	0.6
9	0	1	1200	550	0.6
10	2	1	1200	600	0.5
11	2	1	960	550	0.7
12	2	1	1440	550	0.5
13	2	1	960	500	0.6
14	0	1	1200	550	0.6
15	2	1	1440	500	0.6

2.2 Experimental Details

Nexus 410A-II 3-Axis Computer Numerical Method (CNC) machine with the MAZATROL controller is the CNC end milling machine that will be used in this project. The workpieces dimension is $50mm \times 50mm \times 30mm$ are suitable for the tilting table integrated into the structure. The work area and top-value technical data on this CNC machine is created for the best access and highest precision. Detail procedure of experimental setup are stated as below:

1. Prepare the vertical CNC milling machine system. Check and ensure the machine is ready to perform the machining operation.
2. Preparation of $50mm \times 50mm \times 30mm$ rectangular aluminium block in forming tool for CNC end milling.
3. This operation is surface roughing operation and a constant dimension of flat end mill and parameters will be used. The size of a flat end mill with a diameter of 8mm and a total length of 65mm. Meanwhile, there are 4 constant parameters that will be used to run all 13 experiments which are plunge rate = 250, retract rate = 500, step over = 1.5 and spindle speed = 4000rpm.
4. Sending all created code file from simulation in Mastercam X7 to the CNC end milling machine to perform the milling operation.
5. The 15 experiments will be conducted under dry conditions with different parameters of the milling process which are feed rate of 500mm/min, 550mm/min, 600mm/min, cutting speed of 960rpm, 1200rpm, 1440rpm and depth of cut of 0.5mm, 0.6mm, and 0.7mm.
6. The roughed surface of workpieces will be measured three times using the surface roughness tester (Mitutoyo SJ-410) to obtain the value of average roughness surface, Ra.

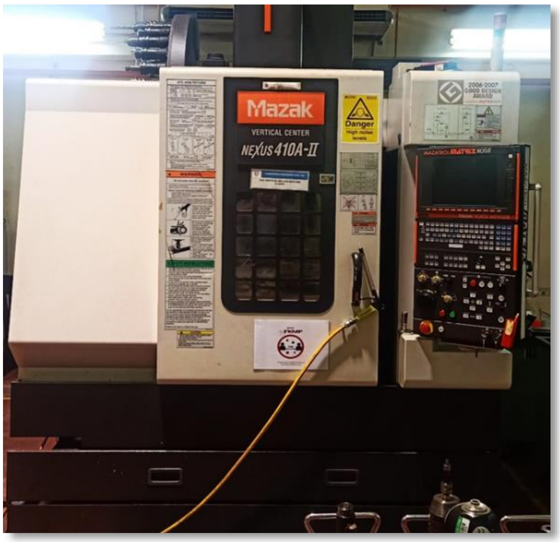

Figure 1: CNC Milling machine

Figure 2: Mitutoyo (SJ-410)

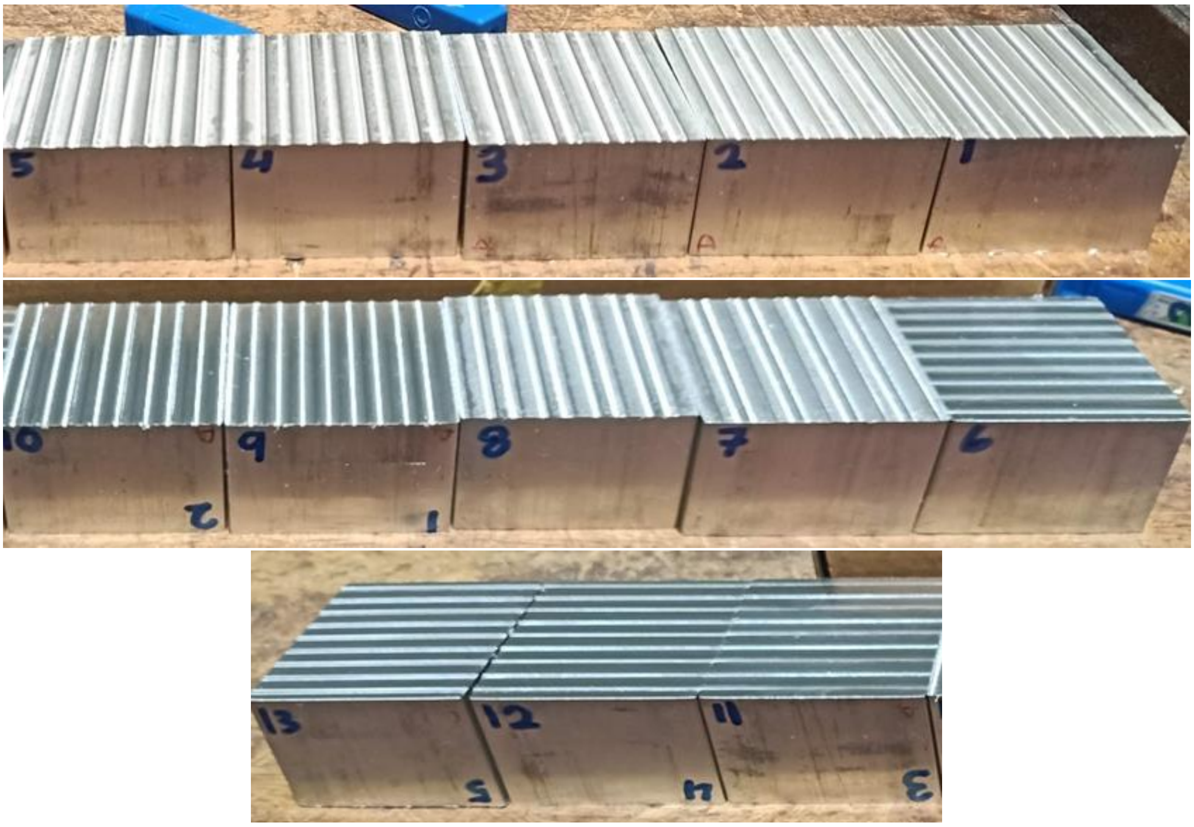

Figure 3: Tested material (Aluminium)

3. Results and Discussion

The purpose of this research is to predict and optimise the cutting parameters that affect the average surface roughness of the centreline of the milled surface. In order to evaluate the influence of cutting parameters on the average roughness of the centreline, RSM was used. The experimental results were transferred into Minitab 19 software. The data collection includes surface roughness as the output response. The analysis divided into three major parts, which is RSM analysis, ANOVA analysis and optimisation analysis.

3.1 Results

Table 3: Experiment Result

No	Parameters			Response
	Cutting Speed, N(rpm)	**Feed Rate, f(mm/min)**	**Depth of Cut, d(mm)**	**Average roughness, Ra (µm)**
1	1200	500	0.5	0.527
2	1200	550	0.6	1.416
3	1200	500	0.7	1.009
4	960	550	0.5	0.815
5	1200	600	0.7	0.917
6	1440	550	0.7	0.725
7	960	600	0.6	1.426
8	1440	600	0.6	1.756
9	1200	550	0.6	1.416
10	1200	600	0.5	1.045
11	960	550	0.7	1.121
12	1440	550	0.5	0.746
13	960	500	0.6	0.643
14	1200	550	0.6	1.416
15	1440	500	0.6	0.940

The parameters were set to achieve best minimum average surface roughness, Ra (0.527µm) found to be at the middle level value of cutting speed (1200rpm), minimum level of depth of cut (0.5mm), and minimum level of feed rate (500mm/min).

3.2 RSM analysis

The second order response surface equations have been fitted using Minitab 19 software for the response variables (Ra). The equation can be given in terms of the uncoded values of the independent variables as the following, Regression Equation in Uncoded Units:

$$\begin{aligned} \mathrm{R_a} = & -45.2 + 0.00691\mathrm{N} + 0.0670\mathrm{f} + 74.5\mathrm{d} - 0.000002\mathrm{N}^2 - 0.000040\mathrm{f}^2 \\ & -44.1\mathrm{d}^2 + 0.000001\mathrm{Nf} - 0.00341\mathrm{Nd} - 0.0305\mathrm{fd} \qquad \text{Eq. 1} \end{aligned}$$

The above model can be used to predict the surface roughness parameters of a specific design point. In order to better understand the interaction of variables on the considered response, a three-dimensional (3D) plot of the measured response was created based on the above model equations. Since the model has three variables, the center level of each graph keeps one variable unchanged. The three-dimensional (3D) graphs are produced to illustrate the relationships occurred between all experimental factors and responses.

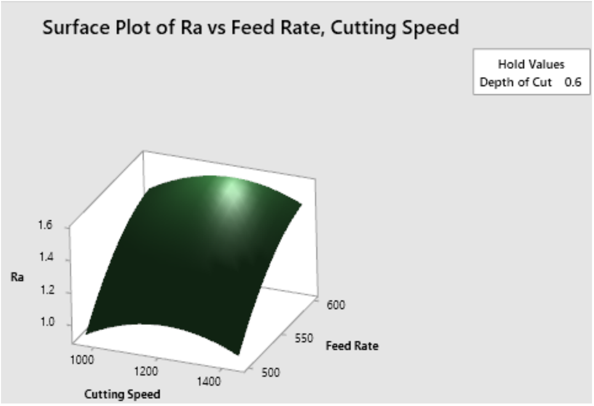

Figure 4 (a)

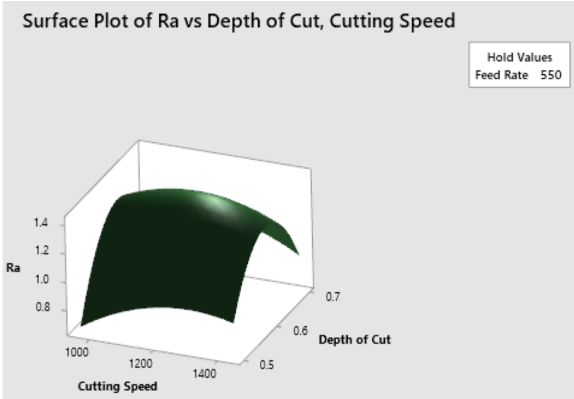

Figure 4 (b)

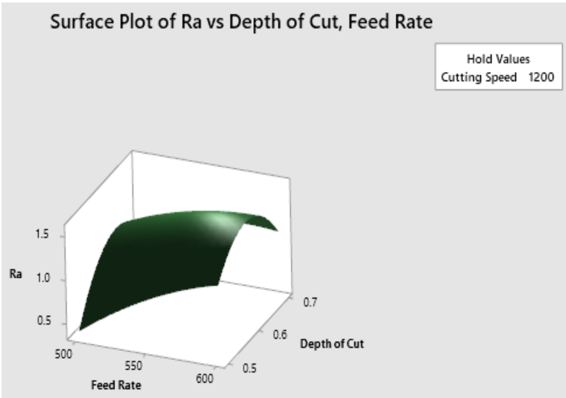

Figure 4 (c)

Figure 4 (a) to Figure 4 (c) give the 3D surface graphs for the roughness parameter Ra. It reveals that Ra increases with increase in cutting speed, feed rate and depth of cut. In Figure 4 (a), when the constant variable (hold values) is depth of cut which set at 0.6mm, it shows that average surface roughness, Ra is at highest point when the cutting speed and feed rate are set as 1200rpm and 600mm/min, respectively. Average surface roughness, Ra increase drastically when feed rate increasing. However, when the cutting speed increasing, Ra slightly increase and then decrease. In Figure 4 (b), the constant variable (hold values) is feed rate which set at 550mm/min, it shows that the average surface roughness, Ra increase and constant at high level as cutting speed increase. Next, average surface roughness, R increase and then decrease when the depth of cut increasing. The 3D graph shows that average surface roughness, Ra is the highest which is 1.4 when the cutting speed and depth of cut are set as 1200rpm and 0.6mm. In Figure 4 (c), the constant variable (hold values) is cutting speed which set at 1200rpm, it shows that the average surface roughness, Ra increase as the feed rate increasing. Next, when the depth of cut increase, the average surface roughness, Ra is increasing and then decrease. The graph shows that the average surface roughness, Ra are at their maximum which is 1.5 when feed rate and depth of cut are set at 600mm/min and 0.6mm.

The big change shows that feed rate is the most significant forming variable influencing the average surface roughness Ra, which is consistent with the analysis in the ANOVA Table 5 below. In addition to the dynamic effect on the cutting force, increasing the feed rate will also cause a large amount of material to be cut in the same unit of time. It also leads to a corresponding increase in the normal contact stress between the tool chip interface and the tool chip contact area. Therefore, the cutting force is found to increase with increasing feed rate. Similarly, an increase in the depth of cut will result in an increase in the working contact length of the tool. Subsequently, the thickness of the chip becomes very large, resulting in an increase in the volume of the deformed aluminium and a higher cutting force is required to cut the chips. As the cutting speed increases, the decrease in force may be due to the increase in the temperature of the cutting plane area, resulting in a decrease in the cutting resistance of the material.

3.3 Response surface regression and ANOVA

Table 4: Response surface regression for Ra versus all parameters

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	1.416	0.146	9.67	0.000	
N	0.0203	0.0897	0.23	0.830	1.00
f	0.2531	0.0897	2.82	0.037	1.00
d	0.0799	0.0897	0.89	0.414	1.00
N^2	-0.124	0.132	-0.94	0.392	1.01
f^2	-0.101	0.132	-0.77	0.479	1.01
d^2	-0.441	0.132	-3.34	0.021	1.01
Nf	0.008	0.127	0.07	0.951	1.00
Nd	-0.082	0.127	-0.64	0.548	1.00
fd	-0.153	0.127	-1.20	0.283	1.00
R-Sq = 81.82%					

The tests showing significant regression and model coefficients were done to show goodness of the fit for obtained model. These tests had been summarised with help of analysis of variance which help in identifying factors which significantly affect the response variable. The determination coefficient (R-Sq) is an important coefficient and it has found to be high at 81.82%, which means that response model has a good fit with the actual data as shown in Table 4.

Table 5: Analysis of Variance of Ra

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	1.44713	0.160793	2.50	0.063
Linear	3	0.56690	0.188966	2.94	0.138
Cutting Speed	1	0.00328	0.003280	0.05	0.830
Feed Rate	1	0.51258	0.512578	7.97	0.037
Depth of Cut	1	0.05104	0.051040	0.79	0.414
Square	3	0.76021	0.253402	3.94	0.087
Cutting Speed*Cutting Speed	1	0.05654	0.056544	0.88	0.392
Feed Rate*Feed Rate	1	0.03767	0.037665	0.59	0.479
Depth of Cut*Depth of Cut	1	0.71646	0.716456	11.14	0.021
2-Way Interaction	3	0.12003	0.040010	0.62	0.631
Cutting Speed*Feed Rate	1	0.00027	0.000272	0.00	0.951
Cutting Speed*Depth of Cut	1	0.02673	0.026732	0.42	0.548
Feed Rate*Depth of Cut	1	0.09303	0.093025	1.45	0.283
Error	5	0.32164	0.064329		
Lack-of-Fit	3	0.32164	0.107215	*	*
Pure Error	2	0.00000	0.000000		
Total	14	1.76878			

Analysis of variance (ANOVA) and F-ratio tests have been carried out to check the adequacy (suitability) of the Table 4 model. For brevity, the ANOVA table of Ra is constructed. Table 5 shows the analysis of variance table of the second order model proposed for Ra given in the above equation. Analysis of variance (ANOVA) is used to verify the importance and suitability of the established model. By checking F-value and P-value, it can be seen that feed rate is the factor that has the greatest influence on overall surface roughness, followed by depth of cut. The coefficients in the previous equation represent the relative influence of each factor on the response, where a positive sign represents the ability to increase the response and vice versa. It can be seen that the P-value is less than 0.10, indicating that the model is significant at the 90% confidence level. This means that the model is adequate or suitable for representing the relationship between the processing response and the final CNC milling process parameters at a 90% confidence level.

3.3 Optimisation

Checking the graph in Figure 5 below shows that the residuals generally fall in a straight line, which means that the errors are normally distributed. Furthermore, Figure 6 below shows that there are no obvious patterns or abnormal (unusual) structures. This means that the proposed model is sufficient and there is no reason to suspect any violation of the assumption of independence or constant variance. Since optimisation of machining parameters increases the utility for machining economics and product quality, efforts have been made to estimate optimal machining conditions to produce the best surface quality within experimental limitations. In this context, a response surface optimisation is attempted using Minitab 19 software for centre line average surface roughness in CNC milling. The optimised objective function is established to minimise the average surface roughness, Ra.

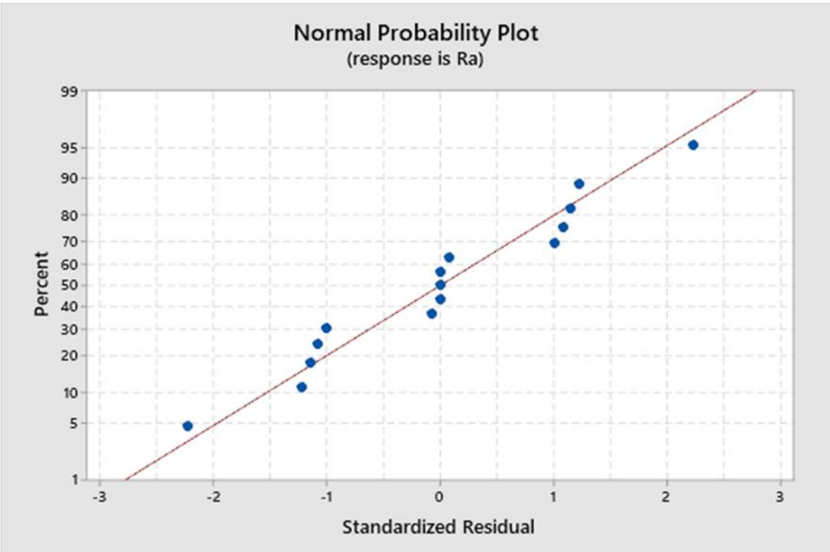

Figure 5: Normal probability plot

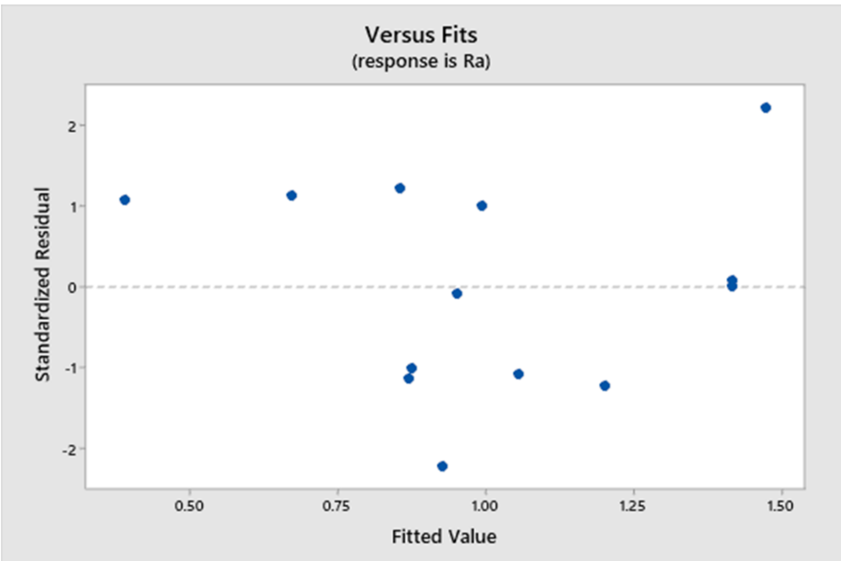

Figure 6: Versus fits

Table 6 below shows the RSM optimisation results of the surface roughness parameters of CNC milling. The optimisation graph in Figure 7 below shows the effect of each factor (column) on the response. The vertical red line on the graph represents the current factor setting. The numbers displayed at the top of the column show the current factor level settings (in red). The horizontal blue lines and the numbers represent the responses for the current factor level. Minitab 19 calculates that centre line average roughness are minimised when factors cutting speed are at 960rpm, depth of cut are at 0.50mm, and feed rate at 500mm/min.

Table 6: Analysis of Variance of Ra

Solution	Cutting Speed	Feed Rate	Depth of Cut	Ra Fit	Composite Desirability
1	960	500	0.5	0.1715	1

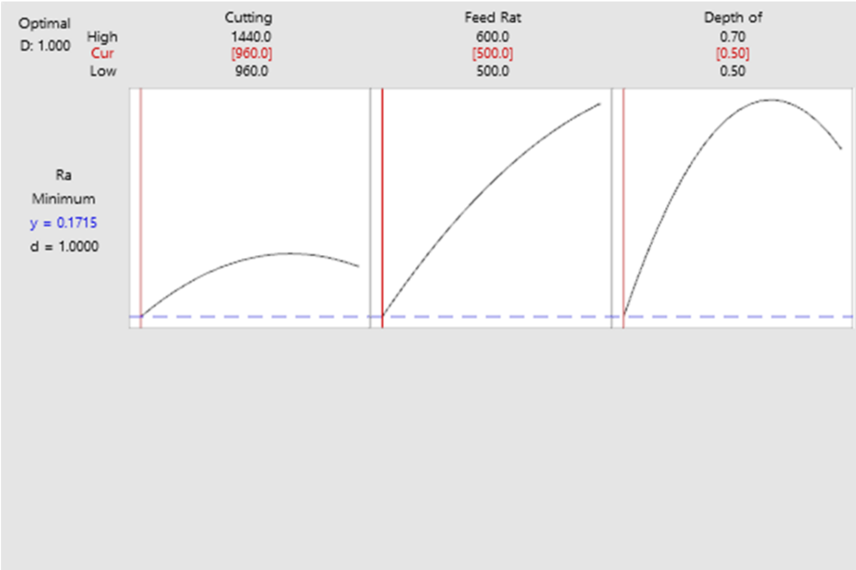

Figure 7: Optimisation plot

4. Conclusion

The effect of cutting speed, depth of cut and feed rate on the surface roughness have been studied and analysed by using response surface methodology technique. The parameters were measured using the experimental design. According to the ANOVA analysis, feed rate affects the most on the surface roughness. Besides, from the 3D graphs that were plotted, the surface roughness changes drastically with the increasing of feed rate regardless of the change of depth of cut. Feed rate, cutting speed and depth of cut are very crucial factors that need to be controlled and chosen carefully. The optimisation plot has been developed by using Response Surface Methodology, RSM for prediction of surface roughness in milling. Finally, an attempt has been made to estimate the optimum machining conditions to produce the best possible surface quality within the experimental constraints.

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References

[1] J. Ribeiro, H. Lopes, L. Queijo, and D. Figueiredo, "Optimization of cutting parameters to minimize the surface roughness in the end milling process using the Taguchi method," *Period. Polytech. Mech. Eng.*, vol. 61, no. 1, pp. 30–35, 2017, doi: 10.3311/PPme.9114.

[2] R. Salami, M. H. Sadeghi, and B. Motakef, "Feed rate optimization for 3-axis ball-end milling of sculptured surfaces," *Int. J. Mach. Tools Manuf.*, vol. 47, no. 5 SPEC. ISS., pp. 760–767, 2007, doi: 10.1016/j.ijmachtools.2006.09.011.

[3] P. Sahoo, "Optimization of Turning Parameters for Surface Roughness Using Rsm and Ga.," *Adv. Prod. Eng. Manag.*, vol. 6, no. 3, pp. 197–208, 2011.

[4] K. K., N. M. M., R. M. M., R. M. R. M., N. N. M. Zuki, and D. R., "Optimization of Surface Roughness in End Milling on Mould Aluminium Alloys (AA6061-T6) Using Response Surface Method and Radian Basis Function Network," *Jourdan J. Mech. Ind. Eng.*, vol. 2, no. 4, pp. 209–214, 2008.

[5] R. K. Beemaraj, "Optimisation of Surface Roughness in Cnc Milling Process Using Optimisation of Surface Roughness in Cnc Milling Process Using Rsm," no. April, 2018.

[6] Y. H. Tan, M. O. Abdullah, C. Nolasco-Hipolito, and N. S. Ahmad Zauzi, "Application of RSM and Taguchi methods for optimizing the transesterification of waste cooking oil catalyzed by solid ostrich and chicken-eggshell derived CaO," *Renew. Energy*, vol. 114, no. PB, pp. 437–447, 2017, doi: 10.1016/j.renene.2017.07.024.

[7] M. Vishnu Vardhan, G. Sankaraiah, M. Yohan, and H. Jeevan Rao, "Optimization of Parameters in CNC milling of P20 steel using Response Surface methodology and Taguchi Method," *Mater. Today Proc.*, vol. 4, no. 8, pp. 9163–9169, 2017, doi: 10.1016/j.matpr.2017.07.273.

[8] P. Mishra, "What is Milling Machine - Operation, Parts and Types. - Mechanical Booster," 2016. https://www.mechanicalbooster.com/2016/12/what-is-milling-machine-operation-parts-types.html (accessed Jan. 05, 2021).

[9] J. M. Manufacturing, "What CNC Milling Machine to Buy - Tips for Choosing Your First CNC Milling Machine | CNCLATHING," 2020. https://www.cnclathing.com/guide/what-cnc-milling-machine-to-buy-tips-for-choosing-your-first-cnc-milling-machine-cnclathing (accessed Jan. 05, 2021).

[10] CustomPartNet, "Milling Process, Defects, Equipment," 2021. https://www.custompartnet.com/wu/milling (accessed Jan. 05, 2021).

[11] N. M. N. Pa, A. A. D. Sarhan, and M. H. A. Shukor, "Optimizing the cutting parameters for better surface quality in 2.5D cutting utilizing titanium coated carbide ball end mill," *Int. J. Precis. Eng. Manuf.*, vol. 13, no. 12, pp. 2097–2102, 2012, doi: 10.1007/s12541-012-0277-y.

[12] O. Bologa, R. E. Breaz, S. G. Racz, and M. Crenganiş, "Decision-making Tool for Moving from 3-axes to 5-axes CNC Machine-tool," *Procedia Comput. Sci.*, vol. 91, no. December 2016, pp. 184–192, 2016, doi: 10.1016/j.procs.2016.07.056.

[13] H. P. Rao, "Optimization of CNC End Milling Process Parameters for Aluminium 6061 Alloy using Carbide Tool Material by Design of Experiments," *IJIRST-International J. Innov. Res. Sci. Technol.*, vol. 3, no. 11, pp. 84–90, 2017, [Online]. Available: www.ijirst.org.

[14] "Cnc drilling & milling operations." https://www.slideshare.net/krishnamrajujampana/cnc-drilling-milling-operations (accessed Jan. 07, 2021).

[15] "Calculation for Cutting Speed, Spindle Speed and Feed | NS TOOL CO.,LTD." https://www.ns-tool.com/en/technology/technical_data/cutting_speed/ (accessed Jan. 07, 2021).

[16] M. Cloud, "Introduction to Milling Tools and their Application Identification and application of cutting tools for milling," 2016.

[17] D. Yang and Z. Liu, "Surface topography analysis and cutting parameters optimization for peripheral milling titanium alloy Ti-6Al-4V," *Int. J. Refract. Met. Hard Mater.*, vol. 51, pp. 192–200, 2015, doi: 10.1016/j.ijrmhm.2015.04.001.

[18] K. Bouacha, M. A. Yallese, T. Mabrouki, and J. F. Rigal, "Statistical analysis of surface roughness and cutting forces using response surface methodology in hard turning of AISI 52100 bearing steel with CBN tool," *Int. J. Refract. Met. Hard Mater.*, vol. 28, no. 3, pp. 349–361, May 2010, doi: 10.1016/j.ijrmhm.2009.11.011.

[19] A. Badr, "General Introduction to Design of Experiments (DOE)," *Wide Spectra Qual. Control*, no. June, 2011, doi: 10.5772/23878.

[20] M. N. Islam and A. Pramanik, "Comparison of Design of Experiments via Traditional and Taguchi Method," *J. Adv. Manuf. Syst.*, vol. 15, no. 3, pp. 151–160, 2016, doi: 10.1142/S0219686716500116.

[21] J. Zable, "Minitab Launches New Minitab® 19 Statistical Software | Minitab," 2019. https://www.minitab.com/en-us/about-us/press-releases/minitab-launches-new-minitab-19-statistical-software/ (accessed Jan. 07, 2021).

[22] "MASTERCAM MACHINE SIMULATION TUTORIAL," 2018. Accessed: Jan. 07, 2021. [Online]. Available: http://www.mastercam.com/companyinfo/legal/LicenseAgreement.aspx.

[23] B. S. Reddy, J. S. Kumar, and K. V. K. Reddy, "Optimization of surface roughness in CNC end milling using response surface methodology and genetic algorithm," *Int. J. Eng. Sci. Technol.*, vol. 3, no. 8, pp. 102–109, 2011.