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The Influence of Machining Parameters using Cryogenic Cooling System

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Abstract. Coolant is a part of the cutting fluid used in the machining process. Application of cutting fluid in the industry causes environmental pollution problems. One of the sustainable cooling techniques is a CO_2 cryogenic cooling system, which can reduce the effects of cutting fluids. This study aims to conduct mathematical modelling of surface roughness. Machining performance using CO_2 as a cooling technique was used to measure surface roughness. Variations in machining parameters are cutting speed (V_c), radial depth of cut (a_r), and axial depth of cut (a_x). Mathematical modelling was present in this study. The minimum surface roughness, resulted by using Response Surface Methodology (RSM) is the surface quality 0.712 µm. This result was achieved using the cutting speed of 31.10 m/minute, the axial depth of cut 5 mm, and the radial depth of cut 0.2 mm. The minimum surface roughness value was achieved with optimized machining conditions with the desirability of 87.5%

INTRODUCTION

The manufacturing industries always lead to higher productivity, ensuring the best quality for their products. In conventional machining, friction and higher temperatures in the cutting zone are the main problems, which is always a challenge, resulting in low dimensional accuracy and impairs product surface integrity. To solve the high cutting temperature can by choosing the right cutting fluid. Conventional cutting fluid applications cannot effectively remove heat due to failure to penetrate the tool interface, especially at high-speed machining [1]. Traditional cutting fluid is also not very useful. It causes significant environmental problems due to chemical damage from cutting fluids at high temperatures and contaminates water and soil during large discharges. The phenomena also impose a high cost for regulating the cooling system because it must be stored, pumped, filtered, and recycled when used [2].

Based on the application and how to choose the coolant, it was significantly affecting the workpiece's quality and the wear of the tools used. Applying the right cutting fluid results in better machine surface quality, and this can prevent high temperatures in the cutting area and keep chips away from the cutting area [3]. Several cryogens are often used, such as liquid nitrogen and CO_2 gas as a coolant during the machining process. Cryogenic cooling system techniques that use cutting fluids at low temperatures such as liquid nitrogen (−196°C) and carbon dioxide (−78.5°C) have been under research recently. [4][5].

The cryogenic cooling technique is a continuous cooling process to reduce the occurrence of high temperatures in the cutting area. The benefits of this cryogenic cooling technique have been around for centuries. Initially, liquefied gas (LN_2) was most often used as a coolant due to its wide availability. The first use of liquefied CO_2 gas as a coolant in machinery was reported by Reitz in 1919 [6]. The cryogenic cooling system is more efficient, economical, and

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environmentally friendly than the conventional coolant, especially in mass production [7]. Coolants and lubricants assist many cooling systems in improving machining performance in the machining process. Carbon dioxide (CO_2) and liquid nitrogen (LN_2) used as cryogenic coolants, and the performance of these coolants was compared to see the tool wear. The results of cryogenic machining using liquid nitrogen showed reduced tool wear in the machining of AISI 4140 steel materials. They also explained that a cryogenic cooling technique that uses carbon dioxide as a coolant helps to improve chip removal. [8].

One of the essential factors is surface quality in analyzing machine components quality and reliability during their lifetime [9][10]. The surface quality of the machined product can be determined by analyzing the residual stress and surface roughness [11][12][13]. In the process of machining a component, the surface quality of the component can be affected by several things, including the cutting process, machine tools, cutting variables, and cutting conditions. [14].

Operation The machining process can be optimized, validated and simulated using mathematical modelling. Using mathematical models also reduces the time to carry out costly and extensive research and optimizes complex processes such as in the field of cryogenic machining. Optimization of machining variables is necessary to obtain the desired surface quality [15][16]. Statistical modelling and computational techniques estimate the surface integrity variables in the machining process using a cryogenic cooling system. [17]. Several researchers have made mathematical models of the machining process when using a cryogenic cooling technique [18][19][20][21]

METHODOLOGY

In this study, material testing was carried out on a milling machine. The cutting tool used the HSS end mill has 4 flutes, the diameter of the cutting tool is 10 mm, while the helical angle of the cutting tool is 60°. The test material in this study is S50C medium carbon steel and the dimensions for this S50C dimension are 25 x 100 x 100 mm. This milling machine was carried out under CO_2 cryogenic cooling system. CO_2 cryogenic cooling system is considered as one of the cooling systems for machining processes that are environmentally friendly.

In a CO_2 cryogenic cooling system, CO_2 gas is supplied from the main tube and channelled through a high-pressure hose. The CO_2 regulator is installed on the main tube to keep the CO_2 flow pressure constant at 43.5 psi. At the end of the hose is installed a nozzle with a diameter outlet 2 mm. The distance between the nozzle and the cutting zone was fixed with a distance of 50 mm.

In these machining variables studied were cutting speed (V_c), radial depth of cut (a_r), and axial depth of cut (a_x). Meanwhile, arithmetic surface roughness (Ra) is a response variable. The machining process can be seen in **FIGURE 1.** The surface roughness value is obtained from measurements at three points, and then the average value is taken for one surface roughness value.

FIGURE 1. The machining process

Mathematical Modelling of Surface Roughness using RSM

In this study, the experiment was designed in Response Surface Methodology (RSM) based on Central Composite Design (CCD). The CCD used is rotatable. Five-level three variables CCD was employed. The experiment requires 20 runs consisting of 8 factorial points, 6 axial points and 6 repetition points in the centre. The distance between the centre points and the axial points is called the rotatable radius or α, the value $\alpha = (2k)^{1/4}$, where k is the number of input variables. The code value for each level obtain from Equation 1, where x is the code value at level, x_n is the variable value at level n, x_{n1} is the variable value at level n + 1, and x_{no} is the variable value at the middle level. Input variables and code level values are shown in **TABLE 1**. The experimental design in actual factor and surface roughness measurement results present in **TABLE-2**.

$$x = \frac{\ln x_n - \ln x_{n0}}{\ln x_{n1} - \ln x_{n0}} \tag{1}$$

TABLE 1. Input variables and coded levels for CCD

Input Variables		**Code Variables Levels**				
		-α	**-1**	**0**	**+1**	**+ α**
Cutting Speed	V_c (m/min)	13.12	16.34	22.54	31.10	38.74
Radial depth of cut	a_r (mm)	0.15	0.20	0.32	0.50	0.68
Axial depth of cut	a_x (mm)	3.95	5.00	7.07	10.00	12.67

TABLE 2.Experiment data and surface roughness result.

No	**Experiment Data – Actual Factors**			**Surface Roughness Ra (µm)**
	Vc – m/min	**a_r (mm)**	**a_x (mm)**	
1	16.34	0.20	5.00	0.950
2	31.10	0.20	5.00	0.625
3	16.34	0.50	5.00	0.962
4	31.10	0.50	5.00	0.757
5	16.34	0.20	10.00	1.061
6	31.10	0.20	10.00	0.672
7	16.34	0.50	10.00	1.193
8	31.10	0.50	10.00	0.982
9	13.12	0.32	7.07	1.289
10	38.74	0.32	7.07	1.076
11	22.54	0.15	7.07	0.968
12	22.54	0.68	7.07	1.354
13	22.54	0.32	3.95	0.965
14	22.54	0.32	12.67	1.200
15	22.5	0.32	7.07	1.301
16	22.5	0.32	7.07	1.679
17	22.5	0.32	7.07	1.459
18	22.5	0.32	7.07	1.735
19	22.5	0.32	7.07	1.174
20	22.5	0.32	7.07	1.787

To get a surface roughness mathematical model, we can get it from the Equation (2) where y is the estimated response based on the second-order Equation. b_0 is a coefficient Constanta, b_1 to b_3 is a linear coefficient, b_{11} to b_{33} is the quadratic Equation, b_{12} to b_{23} is an interaction coefficient, and x_1 to x_3 are the coded values of the surface roughness variables.

$$y = b_0 x_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_{12} x_1 x_2 + b_{13} x_1 x_3 + b_{23} x_2 x_3 + b_{11} x_1^2 + b_{22} x_2^2 + b_{33} x_3^2 \tag{2}$$

RESULT AND DISCUSSION

In the Response Surface Methodology modelling, we carried out analysis ANOVA to measure the statistical significance of the machining parameters for the response model which means that if it has a p-value less than 0.05, it has a significant impact on the model. We analyze at a 95% confidence interval. We can see the mathematical surface roughness model equation first-order in the form of coded factors in Equation (3).

$$y = 0.1088 + 0.1181x_1 + 0.0926x_2 - 0.0751x_3 \quad (3)$$

TABLE 3 shows the ANOVA results from the first-order model. The ANOVA table shows that the p-value number is 0.2101 in the model, which is not significant, and the F-Value value results in a matter of 3.35 on the Lack of Fit and this is not significant. Because the Model and Lack of Fit are not significant for the first order and we cannot use as surface this roughness modelling, therefore, it was upgraded to the second order. **TABLE 4** shows the results of the ANOVA for the second-order.

TABLE 3. First-order model ANOVA of surface roughness.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	0.3847	3	0.1282	1.68	0.2102	not significant
A-Cutting Speed	0.1906	1	0.1906	2.50	0.1331	
B-Radial depth of cut	0.1172	1	0.1172	1.54	0.2325	
C-Axial depth of cut	0.0769	1	0.0769	1.01	0.3297	
Residual	1.22	16	0.0761			
Lack of Fit	1.07	11	0.0975	3.35	0.0964	not significant
Pure Error	0.1456	5	0.0291			
Cor Total	1.60	19				

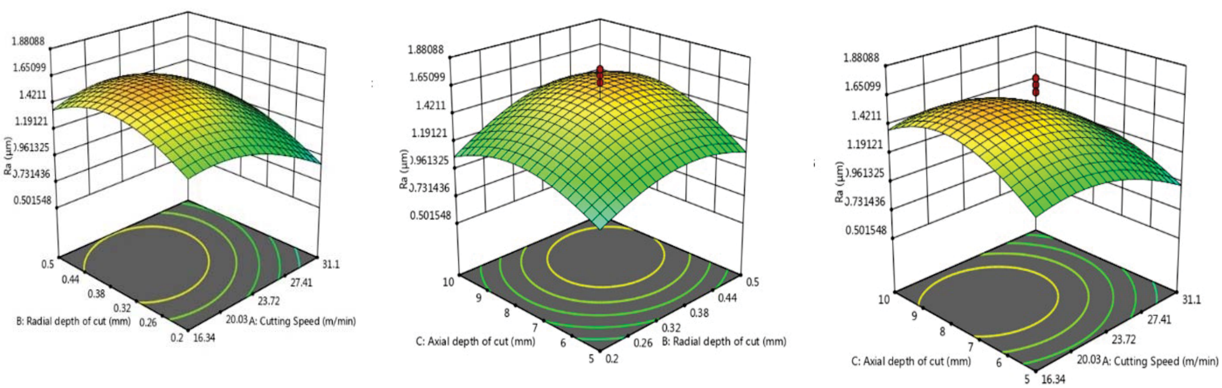
TABLE 4. Second-order model ANOVA of surface roughness

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	1.24	9	0.1377	3.79	0.0247	significant
A-Cutting Speed	0.1906	1	0.1906	5.25	0.0449	
B-Radial depth of cut	0.1172	1	0.1172	3.23	0.1026	
C-Axial depth of cut	0.0769	1	0.0769	2.12	0.1762	
AB	0.0243	1	0.0243	0.6700	0.4321	
AC	6.156E-06	1	6.156E-06	0.0002	0.9899	
BC	0.0107	1	0.0107	0.2944	0.5993	
A^2	0.2666	1	0.2666	7.34	0.0219	
B^2	0.3072	1	0.3072	8.46	0.0156	
C^2	0.4063	1	0.4063	11.19	0.0074	
Residual	0.3631	10	0.0363			
Lack of Fit	0.2175	5	0.0435	1.49	0.3351	not significant
Pure Error	0.1456	5	0.0291			
Cor Total	1.60	19				

The F Model value from the ANOVA table is 3.79, and this indicates that the model is significant or feasible to use because there is only 0.0247 or 2.47% probability that the F-value of 3.79 can occur due to noise. If the P-Value of the Model is less than 0.0500, the model is significant. The values of the coded factors A, A^2, B^2, C^2 are significant model variables. If the F-value of the model is more than 0.1000, it indicates that the model is not significant, the model and we can upgrade to a higher-order. The F Lack of Fit value from the ANOVA table is 1.49, and this indicates that the Lack of Fit is relatively insignificant to pure error because there is only 0.3351 or 33.51% the possibility that the F-Value Lack of Fit of 1.49 can occur because of the noise. The Equation of the mathematical model in the form of coded factors for second-order shown in Equation (4) below.

$$y = 0.4161 - 0.1181x_1 + 0.0926x_2 + 0.0751x_3 + 0.0551x_1x_2 + 0.0009x_1x_3 - 0.0366x_2x_3 - 0.1360x_1^2 + 0.1460x_2^2 + 0.1679x_3^2 \quad (4)$$

The response surface graph for the roughness parameter Ra obtained using the Design-Expert program can be seen in **FIGURE 2**. From Equation (4) and the disturbance plots, as shown in **FIGURE 3**, can explain the effect of the three machining parameters used in the cryogenic cooling system machining conditions on surface roughness. Of the three machining parameters used that affect the value of surface roughness, the cutting speed parameter has the most significant effect followed by Radial DoC and Axial DoC. The surface roughness of the specimen becomes smoother as the cutting speed increases..



(a) (b) ©

FIGURE 2. Response graphics surface roughness Ra (a) radial DoC vs cutting speed (b) axial DoC vs cutting speed (c) axial DoC vs radial depth of cut

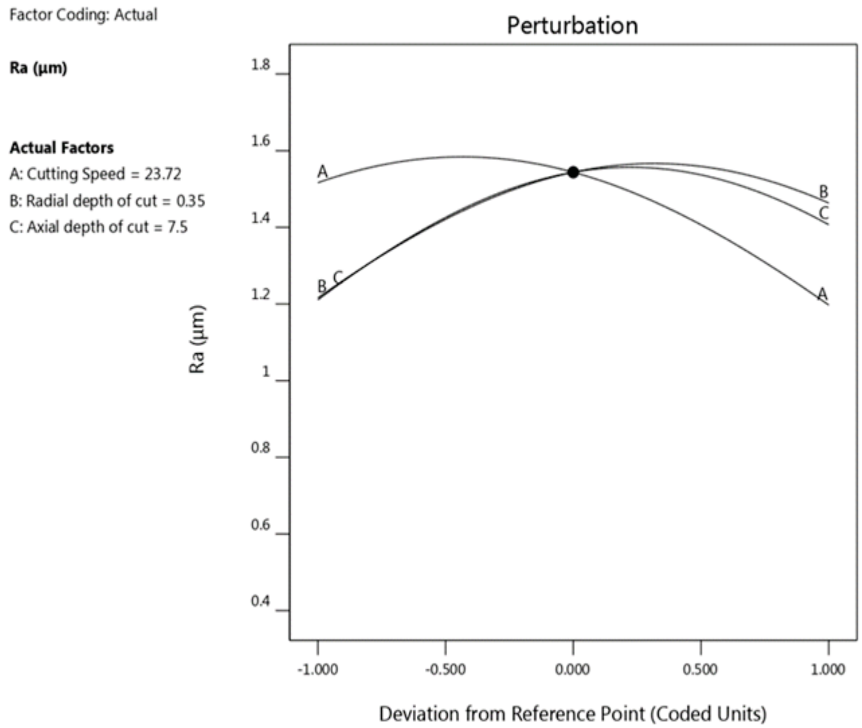


FIGURE 3. The perturbation plot for surface roughness

To get the optimum surface roughness value from the minimum surface roughness of 0.712 µm, which can gain from cutting speed of 31.10 m/minute, the axial depth of cut of 5 mm, and radial depth of cut 0.2 mm. The minimum surface roughness value we can achieve with optimized machining conditions with the desirability of 87.5%, as shown in **TABLE 5**.

TABLE 5. Optimum machining condition for minimum surface roughness value.

Number	Cutting Speed	DoC Radial t	DoC Axial	Ra	Desirability	
1	31.100	0.200	5.000	0.712	0.875	**Selected**
2	31.017	0.200	5.000	0.716	0.871	
…	…	…	…	…	…	

CONCLUSIONS

Machining parameters in this study, cutting speed (V_c), radial depth of cut (a_r), and axial depth of cut (a_x) are parameters that have a strong influence on surface roughness. In particular, the cutting speed is the parameter that most influences the surface roughness, followed by the radial cutting depth and the smallest effect is the axial cut depth to this surface roughness.

The optimum surface roughness value from the minimum surface roughness of 0.712 µm, which can gain from cutting speed of 31.10 m/minute, the axial depth of cut of 5 mm, and radial depth of cut 0.2 mm. The minimum surface roughness value we can achieve with optimized machining conditions with the desirability of 87.5%

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