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Optimization of CNC milling parameters using the response surface method for aluminum 6061

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Abstract
The manufacturing sector is constantly seeking ways to optimize the machining process, specifically for 3-axis CNC machines. This study aims to identify the optimal parameter values that result in the lowest roughness and the highest process capability in 3-axis CNC milling. The roughness level (Ra) of the product is primarily influenced by factors such as feed rate, spindle speed, and depth of cut. Additionally, the reliability of the machining process was analyzed to evaluate its ability to consistently achieve low roughness values and to validate the process capability of the VH850L3 series 3-axis CNC milling machine. The suggested approach for this analysis was the RSM central composite design method, which involved conducting experiments under various input conditions. The results indicated that the feed rate had the most significant impact on roughness, followed by the spindle speed, while the depth of cut had no effect. The parameters that resulted in the lowest roughness response were a spindle speed of 2589.76 rpm, a depth of cut of 0.159 mm, and a feed rate of 247.731 mm/min. These parameter values were tested on a 3-axis CNC machine, and the resulting data exhibited variations. Data processing revealed that the machine still performed optimally in the machining process, as indicated by the value of $1 < Cp < 1.33$. However, the milling process deviates from the standard target, as the response value shows significant variation with a Cpk value <1.

Keywords:
CNC, Ra, RSM, Cp, Cpk.

1 Introduction

The Computer Numeric Control (CNC) milling machine consists of two or more axes that dictate tool movement. These movements can be linear (straight lines) or circular (following circular paths). Typically, the X, Y, and Z axes control linear movements, while the A, B, and C axes control circular movements. The CNC milling process relies on the spindle's rotational speed and the control of the feed rate to achieve precise machining [1]. To enhance consumer value, it is crucial to ensure high-quality machining during the manufacturing process.

In recent decades, CNC machines have become indispensable owing to their high reliability, increased accuracy, and improved productivity levels. Compared with conventional milling processes, CNC milling offers greater flexibility in selecting the parameter levels. Various milling processes are employed in the manufacturing industry, including peripheral, face, and end milling [2-3]. Each machining process requires regulation of numerous parameters. These parameters can be classified as controllable or uncontrollable. Controllable parameters such as spindle speed, cutting speed, rake angle, depth of cut, and feed rate can be adjusted as needed. On the other hand, uncontrollable parameters, such as tool wear, surface roughness, vibration, and geometric accuracy, cannot be directly controlled.

Achieving optimal surface roughness is a critical aspect of the milling process to produce high-quality products. Surface roughness in milling processes typically exhibits distinct characteristics, making it the focus of many research studies.

One study recommends using the smallest feed rate during the finishing process and a larger feed rate during roughing to optimize time and cost in the milling process [4]. The feed rate is identified as the most crucial machine input parameter influencing surface roughness, surpassing the impact of the depth of cut and spindle speed [5]. Permanent function variations can be calculated by adjusting the diagonal element values to account for parameter and cutting condition variations [6]. Increasing cutting speed results in a reduction in surface roughness when the feed rate is decreased [7]. Utilizing a systematic approach in central composite design proves beneficial as it minimizes the number of required experiments. According to Asiful H. Seikh et al., the surface roughness model indicates that the radial depth of cut contributes the most (45.81%) and has the greatest impact on surface roughness [8]. R. Suresh Kumar et al. also conclude that optimizing machining parameters in low carbon steel milling processes affects surface roughness, Material Removal Rate (MRR), power consumption, and tool life, but with contradictory impacts [9]. Results from ANOVA analysis demonstrate that the parameters significantly affecting surface roughness are spindle speed (42.42%), feed rate (29.40%), and cutting depth (6.59%), respectively. Meanwhile, according to Chi Thien Tran et al., the parameter with the most significant influence on the milling process is the feed rate (92.6%) [10]. By using a backpropagation neural network, the Root Mean Square Error (RMSE) was calculated to be 0.008, which is significantly smaller than the 0.021 obtained with conventional linear regression, as shown by Chen, C.-H, et al. [11]. Analysis of the substrate and machine surfaces using XRD revealed that the broad diffraction peaks mostly consisted of α-Fe, according to Wu et al. [12]. Taguchi design can optimize milling process parameters for surface roughness [13-15]. Other researchers have argued that the response surface method is effective for optimizing data [16-20].

Process capability index is a measure of a product's ability, measured by the actual or potential execution of procedure attributes, with specific goals and parameter points. Cp has become the most frequently used index in practice because it imposes limits on the division of defective item procedures. This is an essential concept in statistical process control that describes the strength of a process to produce components within tolerance limits [21-22].

The literature review of the journal revealed extensive research in the field of machining using optimization methods. This study focused on efforts to optimize surface roughness (Ra) on workpieces using the response surface method. Subsequently, the minimum roughness data obtained from the response surface method were used as actual data in the machining process and processed based on statistical process capability indices to measure the efficacy of the ongoing process. Process capability served as a valuable parameter for consideration.

2 Methods and Implementation

This research aims to investigate the primary factors influencing the surface roughness of 6061 series aluminum with dimensions of 107×70×15 mm (2 pieces). The study employs a 3-axis CNC Milling machine series VH850L3 and an HSS flat end mill with a diameter of Ø 10 mm and 4 flutes. For the CNC milling process, facing or cutting techniques were chosen with clockwise movement to attain a flat surface perpendicular to the cutting rotation axis. The parameters tested included spindle speed, feed rate, and cutting depth. The methodology employed involves the response surface method and mathematical modeling to determine the minimum value of surface roughness. Moreover, the minimum roughness data obtained from the response surface method were utilized as the actual data in the machining process.

The sequential research approach is:

1. Determination of levels for each parameter
2. Experiments are conducted based on central composite design
3. Measurement of surface roughness
4. Analyzing the influence of parameters
5. Determination of the minimum roughness value obtained from response surface method data
6. Experimental runs are conducted with 10 replications using the minimum roughness value data
7. Application of capability process analysis for CNC milling machine optimization
8. Confirmatory runs are conducted to validate the achieved results.

2.1 Controlled and Uncontrolled Parameters

A machining process is greatly influenced by parameters such as spindle speed, feed rate, and depth of cut. Among these parameters, some can be set before the process begins, known as controllable parameters. The parameters in Table 1 of the CNC milling process (23) are varied with attractive values. On the other hand, there are certain parameters that fluctuate based on these parameters, known as uncontrollable parameters. In this study, the controllable factors are spindle speed (A), depth of cut (B), and feed rate (C), with a measurement distance on the surface roughness of 2.5 mm while surface roughness (Ra) becomes the uncontrollable response. The dependent variables in this research include the use of a 3-axis CNC milling machine series VH850L3, which has completed many projects; a flat endmill made of HSS with a diameter of Ø 10 mm and four flutes (Fig. 1); and aluminum duralium 6061. The instruments used in this study include a roughness tester (Surface Roughness Tester Landtek SRT-6200 Gloss Meter SRT6200 Glossmeter) as shown in Fig. 2.

Table 1. Experimental parameters

Parameter	Unit	Low	High
Spindle speed (A)	rpm	1450	2300
Depth of cut (B)	mm	0.5	1.5
Feed rate (C)	mm/min	350	650

Fig. 1. Endmill HSS (10 mm 4 flute).

Fig. 2. Surface roughness tester.

The initial stage of the research involved preparing 14 tools and specimens. Each specimen was used in a single experiment, with a new flat end mill employed for each to ensure minimum surface roughness data.

The next step involved setting the zeropoint using Sentrofix (Fig. 3). The G-code program (Fig. 4) is input into the CNC milling machine to execute the program according to the desired workpiece design (Fig. 5). The software used was the MastercamX5. This process was repeated 14 times to conduct 14 experiments using various parameters.

Fig. 3. Zero setting process.

```
%
O000013
N100 G21
N102 G0 G17 G40 G49 G80 G90
N106 G0 G90 G54 X-118. Y-62.5 S1450 M3
N108 G43 Z50.
N110 Z10.
N112 G1 Z-1.5 F190.9
N114 X11. F350.
N116 G0 Z50.
N118 M5
N120 G91 G28 Z0.
N122 G28 X0. Y0.
N124 M30
%
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Fig. 4. G-code program.

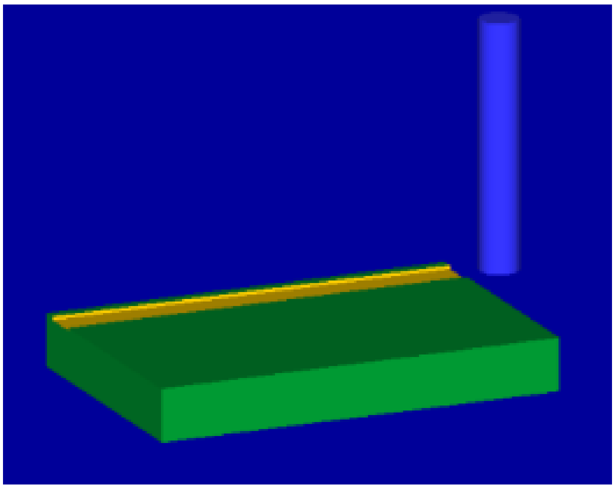

Fig. 5. Simulation of G-code program in MastercamX5.

2.2 Design Matrix

In the first experimental iteration, a central composite design with a two-level factorial, three factors, eight cube points, six center points in the cube, and zero center points in the axial direction were used, as outlined in Table 1. The detailed sequence of experimental runs for the central composite design can be seen in Table 2. In each experiment, a new endmill was used.

Table 2. Runs experimental cental composite design

A (rpm)	B (mm)	C (mm/min)
1450	0.5	350
2300	0.5	350
1450	1.5	350
2300	1.5	350
1450	0.5	650
2300	0.5	650
1450	1.5	650
2300	1.5	650
1875	1	500
1875	1	500
1875	1	500
1875	1	500
1875	1	500
1875	1	500

The second experimental iteration was based on the CNC milling machine's process capability using the data from the experimental parameters with the minimum roughness in Table 5. Subsequently, 10 replications of experiments were conducted, as shown in Table 6.

3 Results and Discussion

After the machining process on the CNC milling machine, surface roughness testing was conducted using a surface roughness tester. Calibration was performed before the surface roughness tester was used. The measurement length (cutoff length) was set to 2.5 mm, and the workpiece was placed on a level surface (Fig. 6). Measurements were repeated three times, and the average of these repetitions was taken to obtain one roughness value for each specimen.

The data obtained from the testing werre analyzed to determine the minimum roughness value and the more dominant influence on the machining parameters.

Subsequently, the results of parameters with low roughness values were elaborated to validate the process capability in CNC milling 3-axis VH850L3 series, whether it operated well or not, by observing the consistency of data on the roughness values of the machining process parameters.

Fig. 6. Data measurement.

3.1 Response Surface Method

The test results data and combinations shown in Table 3 will be further analyzed using the response surface method and ANOVA to determine the influence of parameters on the roughness value. Minitab 20 software was used to expedite the analysis process and statistical calculations. From the 14 experimental runs conducted, maximum, minimum, average, standard deviation, and ratio values for each response and factor in the roughness test are obtained, as shown in Table 4.

By conducting a two-way Analysis of Variance (ANOVA), which consists of calculating the sum of squares, degrees of freedom, means, and F-values, statistical ANOVA data for surface roughness testing are obtained, as shown in Table 4.

Data processing in this experiment was completed using a Minitab 20. In Table 4, it is known that by adjusting the spindle speed and feed rate, there is a significant difference, which has been shown in the table that p-values are 0.013 (>0.05) and 0 (>0,05). The p-value of the feed rate indicated that the feed rate parameter was highly influential, with a p-value of 0. However, unlike the p-value, the depth of cut values has no significant impact, where p-values are 0.611 (<0.05). The lack-of-fit test in this experiment against the model obtained a p-value of 0.652, indicating that H_0 accepted means the regression model matched.

Table 3. Results of surface roughness testing 1st orde

Actual variables			Code variable			Response (y)
X_1	X_2	X_3	A	B	C	
1450	0.5	350	-1	-1	-1	2.902
2300	0.5	350	1	-1	-1	2.439
1450	1.5	350	-1	1	-1	3.012
2300	1.5	350	1	1	-1	2.619
1450	0.5	650	-1	-1	1	8.960
2300	0.5	650	1	-1	1	7.594
1450	1.5	650	-1	1	1	9.438
2300	1.5	650	1	1	1	7.543
1875	1	500	0	0	0	4.711
1875	1	500	0	0	0	5.555
1875	1	500	0	0	0	4.901
1875	1	500	0	0	0	5.906
1875	1	500	0	0	0	5.084
1875	1	500	0	0	0	5.939

Table 4. Data analysis of variance 1st orde

Source	DF	Adj SS	Adj MS	F-value	P-value
Model	3	65.8191	21.9397	94.07	0.000
Linear	3	65.8191	21.9397	94.07	0.000
X_1	1	2.1187	2.1187	9.08	0.013
X_2	1	0.0643	0.0643	0.28	0.611
X_3	1	63.6361	63.6361	272.84	0.000
Error	10	2.3324	0.2332		
Lack-of-fit	5	0.9536	0.1907	0.69	0.652
Pure error	5	1.3788	0.2758		
Total	13	68.1515			

Based on the ANOVA test and the lack of fit model order I test, there are two variables that have a significant influence on the response. So, to proceed with the analysis on the assumption of the phase 2 experiment model, it is necessary to carry out the analysis to see the direction in which the stage 2 experiment will be carried out. The response surface method II model was designed using a central composite design full quadratic. The 2^k factorial design used in the order I design was added with an axial point and center point. It is known that there are three free variables; therefore, it is necessary to add an axis point of as many as 2k, where k is a factor. Therefore, six axial points are required in the study of the surface response model order II.

Data processing is then carried out to see the results of the response surface method order 2. The data processing results are shown in Table 6.

In hypothesis testing, H_0 means that the model fits or there is no lack of fit (>0.005). Meanwhile, H_1 the model does not fit or there is a lack of fit (<0.005).

From the lack of test on the second-order model, the p-value = 0.191 or greater than the significance degree α = 0.05, so there is no reason to reject H_0. This indicated that the regression model was suitable. Based on the analysis results, the model is obtained as shown in Fig. 7.

Ra = -6.17 + 0.00545 X1 + 3.36 X2 + 0.0050 X3 - 0.000001 X12 - 1.117 X22 + 0.000022 X32 - 0.00027 X1 X2 - 0.000005 X1 X3+ 0.00023 X2 X3

Fig. 7. Regression equation.

Table 5. Data analysis of variance 2nd orde

Actual variables			Code variable			Respon (y)
X_1	X_2	X_3	A	B	C	
1450	0.5	350	-1	-1	-1	2.902
2300	0.5	350	1	-1	-1	2.439
1450	1.5	350	-1	1	-1	3.012
2300	1.5	350	1	1	-1	2.619
1450	0.5	650	-1	-1	1	8.96
2300	0.5	650	1	-1	1	7.594
1450	1.5	650	-1	1	1	9.438
2300	1.5	650	1	1	1	7.543
1875	1	500	0	0	0	4.711
1875	1	500	0	0	0	5.555
1875	1	500	0	0	0	4.901
1875	1	500	0	0	0	5.906
1875	1	500	0	0	0	5.084
1875	1	500	0	0	0	5.939
2589.76	1	500	1.68	0	0	2.898
1160.24	1	500	-1.68	0	0	5.91
1875	1.84	500	0.00	1.68	0	5.489
1875	0.16	500	0.00	-1.68	0	2.94
1875	1	752.27	0.00	0.00	1.68	10.848
1875	1	247.73	0.00	0.00	-1.68	1.954

Table 6. Data analysis of variance 2nd orde

Source	DF	Adj SS	Adj MS	F-value	P-value
Model	9	117.714	13.079	28.73	0.000
Linear	3	111.092	37.031	81.34	0.000
X_1	1	6.174	6.174	13.56	0.004
X_2	1	1.833	1.833	4.03	0.073
X_3	1	103.085	103.085	226.44	0.000
Square	3	5.870	1.957	4.30	0.034
X_1^2	1	0.650	0.650	1.43	0.260
X_2^2	1	1.124	1.124	2.47	0.147
X_3^2	1	3.513	3.513	7.72	0.020
2-way interaction	3	0.752	0.251	0.55	0.659
$X_1 * X_2$	1	0.026	0.026	0.06	0.815
$X_1 * X_3$	1	0.723	0.723	1.59	0.236
$X_2 * X_3$	1	0.002	0.002	0.01	0.944
Error	10	4.552	0.455		
Lack-of-fit	5	3.174	0.635	2.30	0.191
Pure error	5	1.379	0.276		
Total	19	122.266			

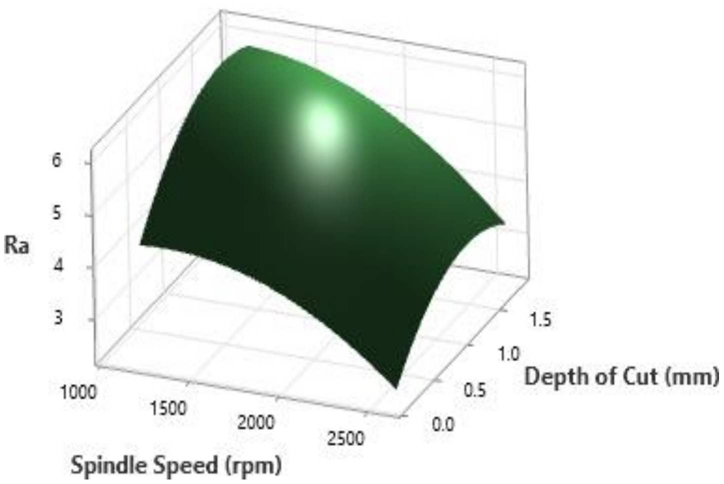

Fig. 8. The surface plot graph of the interaction spindle speed and depth of cut.

The interaction of parameters depicted in Fig. 9 indicates that the minimum roughness is achieved when the depth of cut is at 0.159 mm and spindle speed is at 2589.76 rpm. For the maximum roughness, it occurs at a depth of cut of 1.84 mm and a spindle speed of 1160.24 mm/min. Any deviation from these levels results in adverse effects on the Ra response.

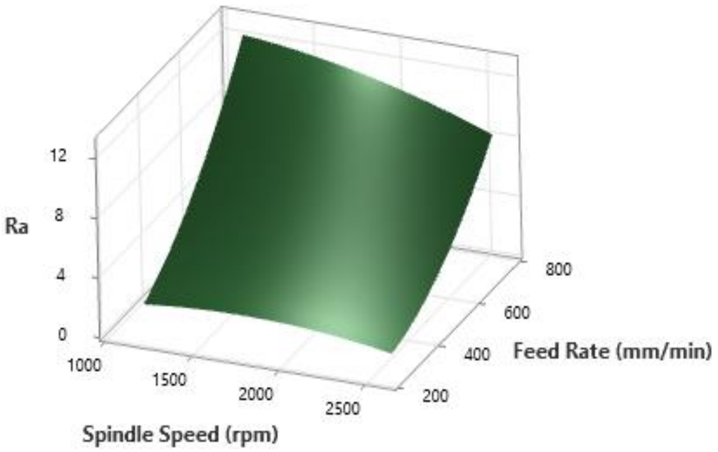

Fig. 9. The surface plot graph showing the interaction feed rate and spindle speed.

In Fig. 10, the minimum value of the interaction parameter between spindle speed and feed rate occurs at spindle speed of 2589.76 rpm and feed rate of 247.73 mm/min. The mutual interaction of the parameters is evident in Table 3, where increasing the spindle speed and decreasing the feed rate resulted in a lower roughness value.

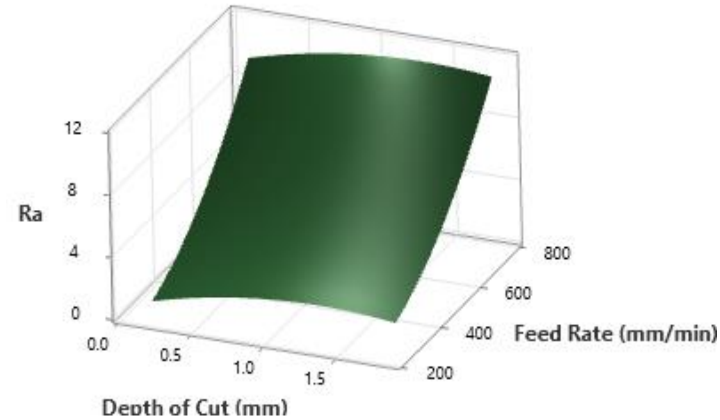

Fig. 10. The surface plot graph illustrating the interaction depth of cut and feed rate.

In Fig. 11, the interaction depicted shows no mutual influence between spindle speed and depth of cut parameters. The minimum value is obtained when the depth of cut is at 0.159 mm and the feed rate is 247.73 mm/min. The maximum value occurred when the depth of cut is at 1.84 mm and the feed rate was 752.269 mm/min.

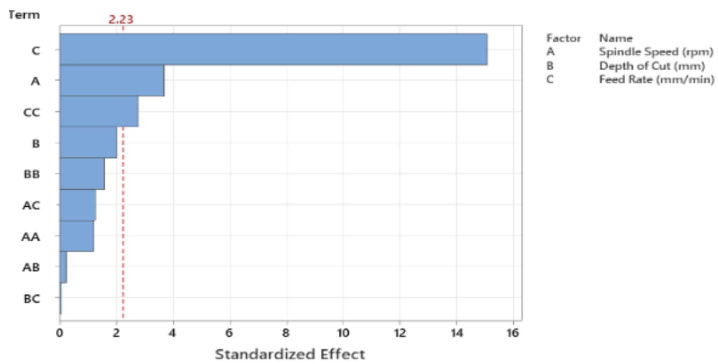

Fig. 11. The Pareto chart showing the influence of parameters on the Ra response.

In Fig. 12, the data values indicate the influence of variable interactions on the response value. As shown in the graph, the feed rate parameter exhibited the greatest influence, with a bar value of 15.048. In contrast, the spindle speed had a bar value of 3.682. The parameter with the least influence on the response value was the depth of cut, with a bar value of 2.006.

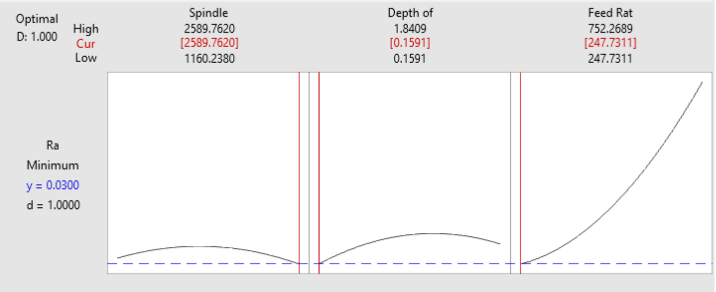

Fig. 12. Minimum response Ra.

Fig. 12, shows the minimum response values the machining process parameters. The lowest roughness response value is indicated as shown in Table 7.

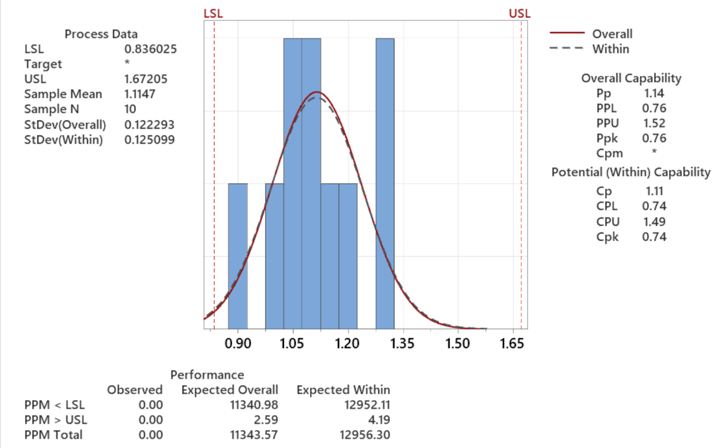

Fig. 13. Chart capabillity process normal.

Table 7. The optimum parameter level for roughness value.

Spindle speed (rpm)	Depth of cut (mm)	Feed rate (mm/min)
2589.76	0.159	247.73

In Table 7, it indicates the optimum parameter levels with minimum response values. Accelerating the spindle speed and decreasing the depth of cut and feed rate resulted in reduced response values.

3.2 Capabillity Process

In this experimental study, several statistical calculations were performed to determine the reliability of the product using the process capability method. The parameters for measurement were based on data with minimum response values. Data collection for the response was conducted with three repetitions of the measurements using a surface roughness tester. In the capability process study, a 4-flute flat endmill is utilized, with each specimen used in a single experiment, employing a new flat endmill for each.

In Fig. 13, data from Table 8 is utilized, detailing the parameters with the lowest response. The data extracted are the averages of three repetitions of roughness measurements for each specimen. The Lower Specification Limit (LSL) and Upper Specification Limit (USL) are obtained from the tolerance value table for roughness specifications according to the task (24). They are applied using the Eq. 1 and Eq. 2.

$$LSL = \frac{y1 + y2 + y3 + \ldots\ldots\ldots + y10}{n} - 25\% = 0.836025\ \mu m \quad (1)$$

$$USL = \frac{y1 + y2 + y3 + \ldots\ldots\ldots + y10}{10} + 50\% = 1.67205\ \mu m \quad (2)$$

Therefore, the USL value is obtained as 0.836025 μm and the LSL value is 1.67205 μm. Based on these roughness values, the face milling task is within the N6 - N7 roughness tolerance specification.

Table 8. RSM data replication results

Spindle speed	Depth of cut	Feed rate	Ra
2589.76	0.159	247.73	0.920
2589.76	0.159	247.73	0.989
2589.76	0.159	247.73	1.120
2589.76	0.159	247.73	1.053
2589.76	0.159	247.73	1.183
2589.76	0.159	247.73	1.155
2589.76	0.159	247.73	1.296
2589.76	0.159	247.73	1.028
2589.76	0.159	247.73	1.289
2589.76	0.159	247.73	1.114

The Cp value of 1.11 indicates that the milling process is considered capable of meeting the specified limits (<1.33). Cpk value of 0.74 suggests that the process is not close to its target value, and a Cpk value of less than 1 indicates the possibility of deviations in machining response values from the standard target, as observed in the varying roughness values.

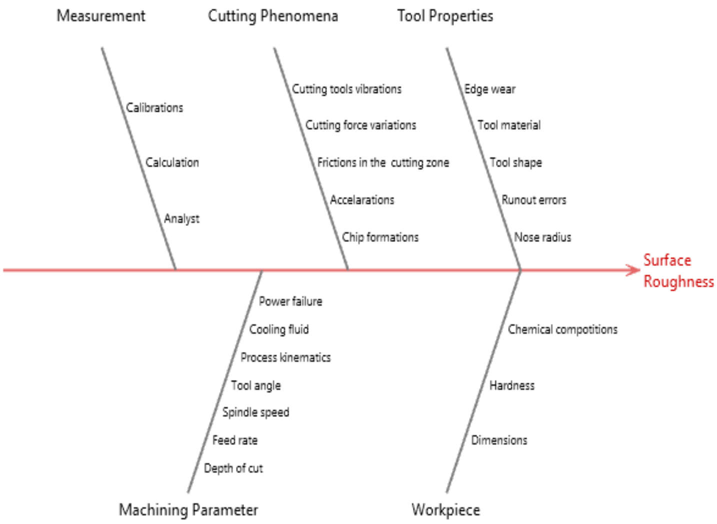

Fig. 14. Fishbone diagram for surface roughness.

The surface roughness results from the milling process, using the parameters suggested by the response surface method, are expected to yield products within specifications. After analyzing the process capability values, it's found that none deviate from the Lower Specification Limit (LSL) or Upper Specification Limit (USL) with $1 < Cp < 1.33$. However, the Cpk values differed, indicating process deviations from the standard target, as shown in Table 8, where the response values varied considerably over a wide range. This discrepancy can be attributed to several factors; for instance, a machine in poor condition can significantly impact the surface roughness outcome of the machining process.

The machine's unstable condition, caused by vibrations from the machine, tool, and spindle, results in vulnerable distance deviations in response values. Additionally, uncontrolled factors such as endmill angle, tool shape, and runout errors also influence surface roughness values. Cooling fluid also affects the milling process and consequently, the response values.

4 Conclusion

Optimizing the machining process parameters for aluminum alloy 6061 using CNC milling machines is of utmost importance, with the response variable being surface roughness. The stability of the roughness was significantly affected by variations in these parameters. Experiments were performed to determine the optimal parameters for the optimization. In addition, ANOVA was utilized to identify the parameters that had the most influence during the machining process. The response surface method, a statistically robust technique with strong theoretical foundations, was employed to vary the parameters effectively.

The capability process method is described in detail to validate the machining process on CNC milling machines. It utilizes parameters with low response values to ensure accuracy and reliability in the validation process.

From these two problems, the data obtained were based on strong theoretical foundations:

1. Minimum surface roughness is achieved with the combination of spindle speed 2589.76, depth of cut 0.159, and feed rate 247.73
2. Adjusting the spindle speed parameter showed a significant effect, as shown in the table with a p-value of 0.004 (>0.05).
3. Adjusting the depth of cut parameter shows no significant difference, with a p-value of 0.073 (>0.05)
4. p-value for the feed rate parameter has a significant difference, with a p-value of 0.000 (<0.05)
5. The milling process is considered capable of meeting the specified limits $1 < Cp < 1.33$
6. Cpk value < 1 indicates deviations in machining process parameters from the standard target, as seen in the varying roughness values
7. The causes of deviation in response values include uncontrolled variables such as machine vibrations, endmill angles, tool shape, runout errors, and cooling fluids.

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