

# Optimizing Parameters of End Mill Cutting Tools for Milling Process

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DOI: <https://doi.org/10.30880/rpmme.2024.05.01.040>

## Article Info

Received: 15 January 2024

Accepted: 15 July 2024

Available online: 15 Sept. 2024

## Keywords

Tool Wear, Milling, Taguchi method,  
Optimization

## Abstract

Tool wear is one aspect that wants to be avoided in machining processes, especially milling. The cutting tools will get worn out when used in a certain period. When the tool wear rate can be minimized, it can give advantages such as cost savings and better performance when milling. An optimum milling parameter can be applied to achieve the goal of minimising tool wear. So, this thesis aims to optimize tool wear by reducing it to the minimum level in the milling process. The Taguchi technique may be used to determine which combination of parameter values works best. One popular strategy for designing straightforward and systematic experiments is the Taguchi method. A conventional Pinnacle milling machine was applied to conduct the research. The SZH10 Olympus optical microscope was used to assess the tool wear on the end mills. The collected data are then examined using Minitab's ANOVA statistical program and the Taguchi method. This investigation aims to determine the ideal milling parameters that reduce end mill tool wear.

## 1. Introduction

Increasing tool life is important to cut production costs as much as possible. Inevitable wear and consequent failure cause the limited life of cutting tools, so the aspects must be studied to achieve a longer tool life, which is referred to as the critical parameter of the cutting process. Cutting tool failure occurs either because they lose their effectiveness due to chipping or plastic deformation or due to slow and steady wear of their cutting edge. Typically, the cutting tool wear threshold value is used to define the tool life requirement. It is obvious that any advancement in tool or work material that increases tool life will be an advantage. Ongoing research is being done to determine how to use cutting tools as much as possible before they break down [1]. Especially for the milling process, a longer tool life includes a systematic approach in order to enhance efficiency and effectiveness.

The cutting tool, feed rate, spindle speed, depth of cut, and other factors are often connected to machining parameters. The impact of tool wear during the machining process also needs to be considered since it might influence the cutting process when the cutting tool comes into contact with the workpiece's material. The rate of tool wear will also affect the item's manufacturing cost [2].

The optimization process is applied to adjust input parameters to ensure the minimum or maximum output can be attained. The primary objective of optimization for machining production line processes could be to evaluate the optimal values of parameter values that will improve productivity, reduce processing costs, improve product quality, and other objective functions [3]. Thus, the aim of the study is to optimize the machining parameters such as cutting speed, feed rate and depth of cut to minimize the tool wear rate





## 1.1 Tool Wear

Tool wear can be described as the rate of flank wear, the change in cutting-edge radius, and the change in tool volume. With reference to the produced workpiece's surface roughness and geometric precision, the impact of machining parameters, such as cutting speed and feed rate, on tool wear was examined. Experimental results show several types of tool wear throughout machining, where abrasive wear and nonuniform flank wear are the main wear mechanisms [4]. When micro-machining, a combination of high cutting speed and low feed rate can reduce tool wear and extend tool life. Low feed rate, however, intensifies the ploughing impact on the cutting zone, leading to decreased surface quality, burr formation, and early tool failure [4]. Fig. 1 shows different types of wear mechanisms, which are flank wear, adhesive wear and micro-chipping.

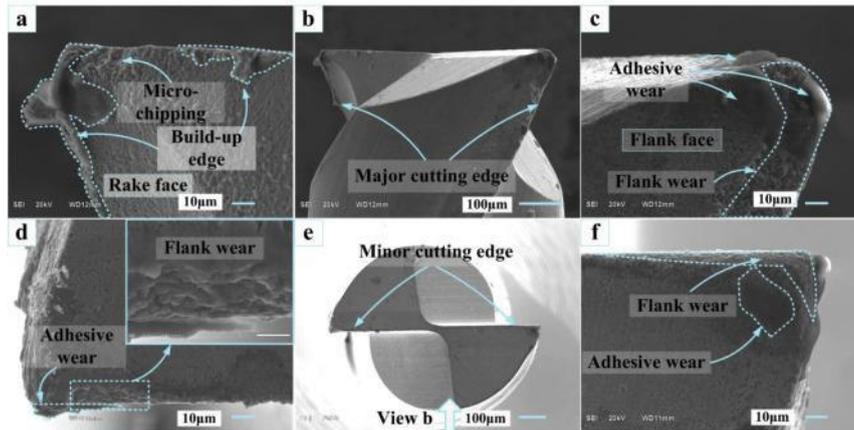


Fig. 1 Types of Milling Tool Wear [5]

## 1.2 Taguchi Method DOE

Known as a resilient design method, the Taguchi Method is a statistical methodology developed by Dr. Genichi Taguchi, a statistician and engineer from Japan. Taguchi devised his approach for designing experiments to ascertain how different process factors will affect the mean and variation of a process performance parameter. Orthogonal arrays are used in Taguchi's suggested experimental design to arrange the variables impacting the process and the levels at which they should be set [6]. Instead of evaluating every conceivable combination as needed by the factorial design, the Taguchi technique tests pairs of combinations [6]. The Taguchi experimental technique is conducted using Minitab software [6].

Minitab provides a complete and best-in-class suite of data analysis and process improvement tools that assist businesses and institutions in finding trends, resolving issues, and gaining valuable insights from data [7]. Thanks to Minitab's unparalleled ease of use, deep insights from data are now easier to obtain than ever. In order to ensure that users get the most out of their analyses and are able to make better, quicker, and more accurate decisions, Minitab also provides a team of highly qualified data analytic experts and services [6].

## 2. Experimental Setup

When a combination of parameters is done manually, this process will become complex and difficult. The Taguchi method is great for the optimization approach to find out the relevant and insignificant factors. To run this method, Minitab 19 software is the medium for analyzing data that can synthesize Taguchi optimization in a smart way. The factors and level for the experiment are shown in Table 1 below. Taguchi L9 orthogonal array method constructed 9 set of experiments which have different combinations of levels for each parameter or factor that can be seen in Table 2.

Table 1 Factors and Level for experiment

Factors	Levels		
	1	2	3
Cutting Speed (rpm)	700	875	1050
Feed Rate (mm/min)	0.10	0.15	0.20
Radial Depth of Cut (mm)	10	5	2.5

**Table 2** Factors and Levels Constructed by Taguchi L9 Orthogonal Array Method

No of Experiment	Control factors and level		
	Cutting Speed (rpm)	Feed Rate (mm/m in)	Radial Depth of Cut (mm)
1	700	200	10.0
2	700	300	5.0
3	700	400	2.5
4	875	200	5.0
5	875	300	2.5
6	875	400	10.0
7	1050	200	2.5
8	1050	300	10.0
9	1050	400	5.0

As part of the project, the Pinnacle conventional milling machine was implemented for the milling process. Before the milling process was done, the end mill diameter was measured with the help of a microscope image measured in the computer software. The milling machine is managed and inspected so that the machine is ready enough to operate for milling procedure. The workpiece chosen is a mild steel block 62 mm long and 50 mm wide that can be clamped on the bed of the milling machine. The high-speed steel (HSS) end mill with a diameter of 10 mm is the 9 cutting tools that are applied for milling the mild steel. The machining process, which is milling for each experiment, will follow the sequence in Minitab constructed by Taguchi L9 orthogonal array method. There will be 9 experiments with different parameters: cutting speed with 700 rpm, 1050 rpm, feed rate with 200 mm/min, 300 mm/min, 400 mm/min and radial depth of cut with 2.5 mm, 5 mm and 10 mm.



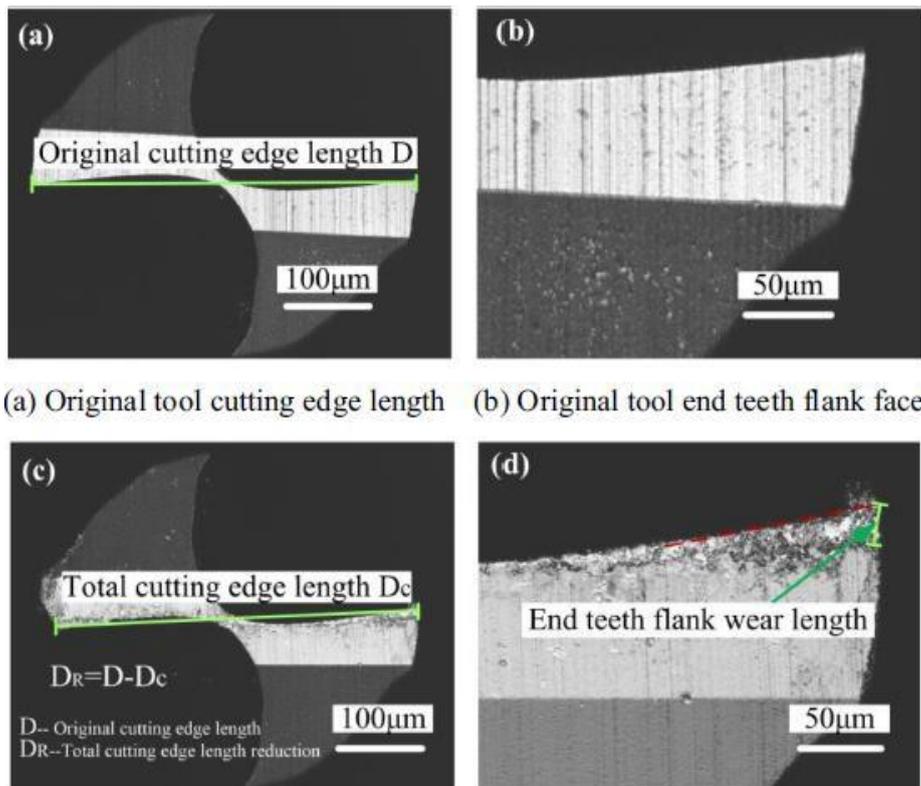
**Fig. 2** Pinnacle Conventional Milling Machine in Milling Lab UTHM

The SZH10 Olympus optical microscope (Fig. 3) was used to examine the end mill tool wear. Microscope calibration was done to ensure accurate measurements if necessary. The end mill was placed on a clean surface for examination and carefully mounted on the microscope stage. The magnification used was 7x, and the image was captured by the microscope imaging software on the computer connected to the microscope. The software contains tools for measuring the image dimensions, so it will be applied to measure the tool's total cutting-edge length.



**Fig. 3** SZH10 Olympus Optical Microscope in Material Characterization Lab UTHM

Tool wear of the endmill can be measured by the difference between the diameter of the end mill before milling and the diameter of the end mill after milling. It is also known as tool wear, which is the total cutting-edge length, as shown in Fig. 4.



**Fig.4** Tool wear total cutting edge length [8]

*Tool Wear Total Cutting Edge Length = Radius of end mill before milling –  
Radius of endmill after milling*

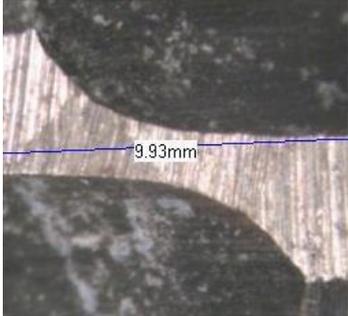
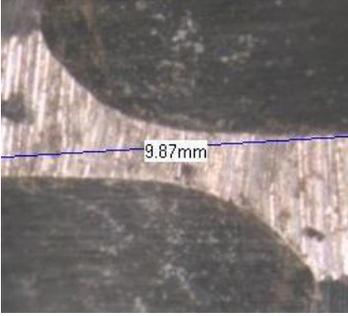
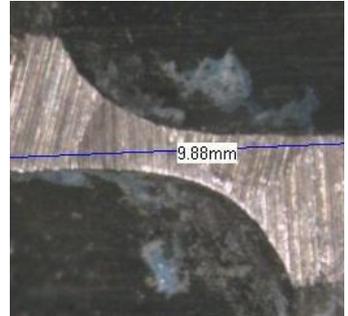
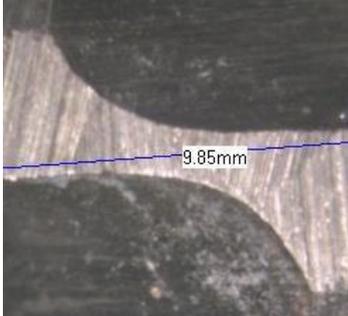
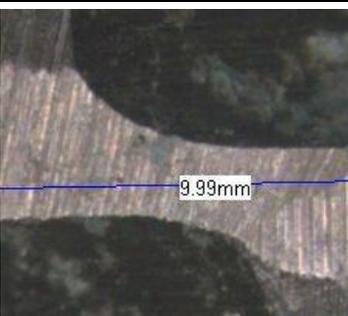
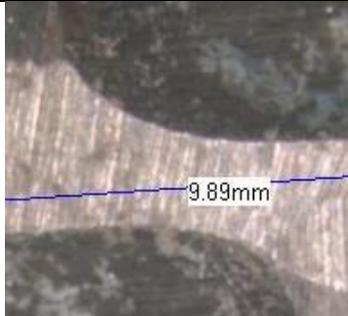
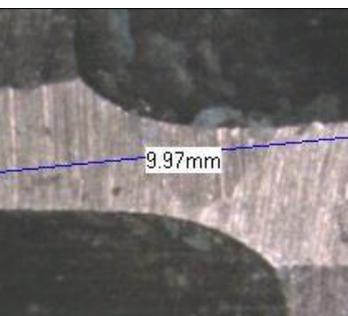
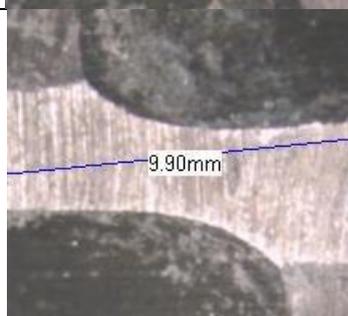
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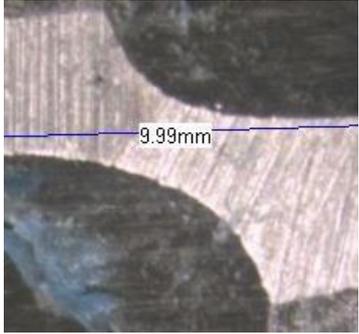
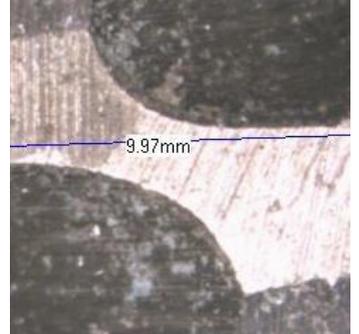
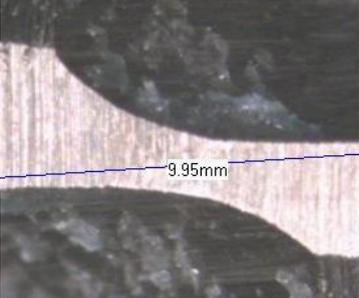
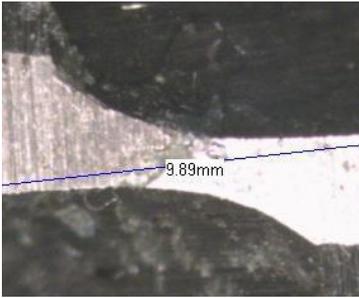
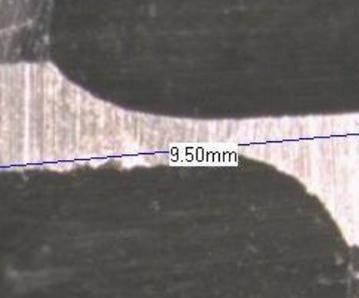
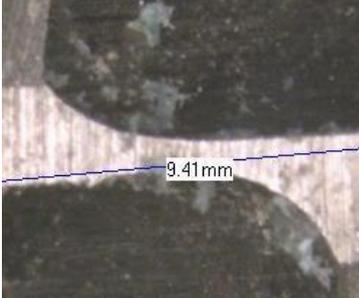
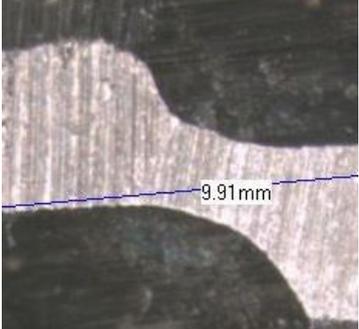
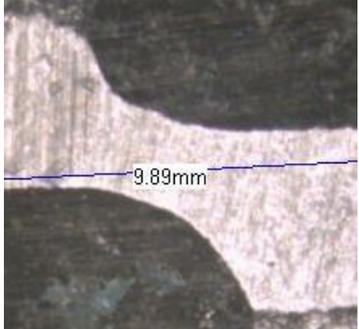
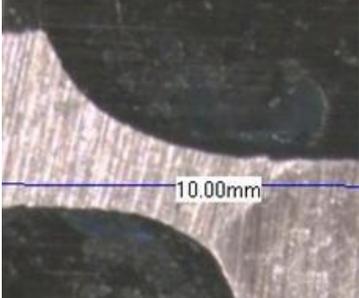
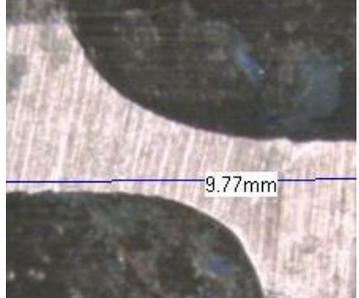
### 3. Results and Discussions

The experiment results are being inserted into the Minitab. The total cutting-edge length of the tool wear is the output response for data gathering.

Table 3 shows the view of the bottom of the end mill before and after the milling process for every number of experiments. The images are generated in the computer connected to the microscope with 7x magnification.

**Table 3** Microscope view for bottom-end mills before and after the milling process

No	Before Milling	After Milling
1		
2		
3		
4		

5		
6		
7		
8		
9		

### 3.1 Data Collection

The data collected from the machining process are shown in Table 4 and Table 5.

**Table 4** Data collection of tool wear total cutting edge length (mm)

No of Experiment	Control factors and level			Tool wear total cutting edge length (mm)
	Cutting Speed (rpm)	Feed Rate (mm/min)	Radial Depth of Cut (mm)	
1	700	200	10.0	0.06
2	700	300	5.0	0.03
3	700	400	2.5	0.10
4	875	200	5.0	0.07
5	875	300	2.5	0.02
6	875	400	10.0	0.06
7	1050	200	2.5	0.09
8	1050	300	10.0	0.02
9	1050	400	5.0	0.23

**Table 5** Tool wear total cutting edge length measurements

No of Experiment	Diameter of End mill Before Milling	Diameter of End Mill After Milling	Tool wear total cutting edge length (mm)
1	9.93	9.87	0.06
2	9.88	9.85	0.03
3	9.99	9.89	0.10
4	9.97	9.90	0.07
5	9.99	9.97	0.02
6	9.95	9.89	0.06
7	9.50	9.41	0.09
8	9.91	9.89	0.02
9	10.00	9.77	0.23

### 3.2 Data Analysis using the Taguchi Method

The optimal condition may be found by applying the Taguchi technique to find the experimental condition with the least variability. The S/N ratio (represented by  $\eta$ ) can express the variation. Because the variability of the features is inversely proportional to the S/N ratio, the experimental condition with the highest S/N ratio is considered as the optimal condition [9]. The rules of experiment design were followed, and the experiments were carried out at random. The objective function described in this investigation is to minimize tool wear and total cutting-edge length. For this reason, the "smaller the better" method was used to determine the S/N ratios.

$$\eta(dB) = -10 \log_{10} \frac{1}{n} \sum_{i=1}^n y_i^2 \tag{2}$$

Where  $y_i^2$  is the  $i^{th}$  value of the response variable (tool wear total cutting edge length).

The experimental data then transformed to the respected S/N ratios, which is shown below in Table 6 with the help of Minitab software.

**Table 6** Experimental Layout of S/N Ratio Value for Tool Wear Total Cutting Edge Length (mm)

No of Experiment	Control factors and level			Tool Wear Total Cutting Edge Length (mm)	S/N Ratio
	Cutting speed (rpm)	Feed rate (mm/min)	Radial depth of cut (mm)		
1	700	200	10.0	0.06	24.4370
2	700	300	5.0	0.03	30.4576
3	700	400	2.5	0.10	20.0000
4	875	200	5.0	0.07	23.0980
5	875	300	2.5	0.02	33.9794
6	875	400	10.0	0.06	24.4370
7	1050	200	2.5	0.09	20.9151
8	1050	300	10.0	0.02	33.9794
9	1050	400	5.0	0.23	12.7654

**Table 7** Response Table for Means

Level	Cutting Speed	Feed Rate	Radial Depth of Cut
1	0.06333	0.07333	0.07000
2	0.05000	0.02333	0.11000
3	0.11333	0.13000	0.04667
Delta	0.06333	0.10667	0.04667
Rank	3	2	1

**Table 8** Response Table for S/N Ratios (Smaller is better)

Level	Cutting Speed	Feed Rate	Radial Depth of Cut
1	24.96	22.82	24.96
2	27.17	32.81	22.11
3	22.55	19.07	27.62
Delta	4.62	13.74	5.51
Rank	3	2	1

Tables 7 and 8 show the average means and S/N ratios for all levels of tool wear and the total cutting edge length. According to the interpretation, the feed rate has the biggest impact on the total amount of tool wear (rank 1), followed by the cutting speed (rank 3), which has the least impact, and the radial depth of cut, which has less impact than the feed rate (rank 2).

### 3.2.1 Analysis of Variance (ANOVA)

This analysis will show the result of which process parameters will affect the response. ANOVA was applied in order to statistically separate significant factors from insignificant ones. Fisher's ratio, denoted as the F-value, is employed in ANOVA to assess the significant impact of a parameter on the chosen tool wear total cutting edge length. A statistically significant relationship is established if the calculated F-statistic exceeds the critical F-statistic at  $\alpha = 0.05$ , determined from the null hypothesis ( $F_{\alpha}(1/2) = 18.513$ ). Conversely, a P-value below 0.05 indicates the statistical significance of the parameters at a 95% confidence level [10]. Table 9 and Table 10 provide the ANOVA for the means of tool wear total cutting edge length.

**Table 9** ANOVA table for Means

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Cutting Speed	2	0.006689	0.006689	0.003344	1.92	0.343
Feed Rate	2	0.017089	0.017089	0.008544	4.90	0.170
Radial Depth of Cut	2	0.006156	0.006156	0.003078	1.76	0.362
Residual Error	2	0.003489	0.003489	0.001744		
Total	8	0.0033422				

**Table 10** Contribution Percentage of Source for Overall Variance

Source	Contribution (%)
Cutting Speed	20.01
Feed Rate	51.13
Radial Depth of Cut	18.42
Residual Error	10.44

The feed rate variable, which makes up for 51.13% of the total variance in tool wear total cutting edge length, has the greatest impact on the overall variance, according to the ANOVA results shown in Table 9 and Table

10. With a contribution of 20.01%, the cutting speed variable comes in second, while the depth of cut variable has a relatively lower degree of significance with the value of 18.42% of the variation in the whole.

Table 9 analysis shows that the P-values for the following feed rate (0.170) cutting speed (0.343) and radial depth of cut (0.362) are above the significance level  $\alpha = 0.05$ , suggesting a 95% confidence level. Thus, it can be said that these three variables have a low impact on tool wear total cutting edge length, so it is not significant. These results are consistent with the respected F-value of 4.90, 1.92 and 1.76 which are less than the F-statistic (18.513) obtained from the null hypothesis.

$$F_{\alpha,1,ferr} = F_{0.05,1,2} \tag{3}$$

### 3.2.2 Analysis of Regression Model

Research with scientific categories usually comes up with regression analysis, which is the relationship between the independent variables and experimental results.

The values for cutting speed, feed rate, and depth of cut (d) were determined through the utilization of Minitab 18.0 software. The regression statistics for these parameters are presented in Table 11.

**Table 11** Regression statistics and Coefficients

Regression statistics		Coefficients	
R-sq	0.3088	Cutting Speed	0.000143
		Feed Rate	0.000283
R-sq (adj)	0.0000	Radial Depth of Cut	-0.00448

Prediction equations for tool wear total cutting edge were established through regression analysis, as outlined in equation 4

$$\text{Tool Wear Total Cutting Edge} = -0.108 + 0.000143 \text{ Cutting Speed} + 0.000283 \text{ Feed Rate} - 0.00448 \text{ Radial Depth of Cut} \tag{4}$$

The determination coefficient for R-sq(R-square) is 0.3088 for tool wear total cutting edge length, which indicates it is not strong enough to indicate the high importance of the projected model.

A graphical method was employed to study the residuals of the model, assessing their adequacy. The sufficiency of the models was determined by examining certain diagnostic charts and testing their statistical

validity. In the normal plots of residuals, the distribution of residuals could be interpreted as following to a straight line, indicating consistent error distribution, as depicted in Figure 5. This observation serves as evidence supporting the significance and accuracy of the developed models.

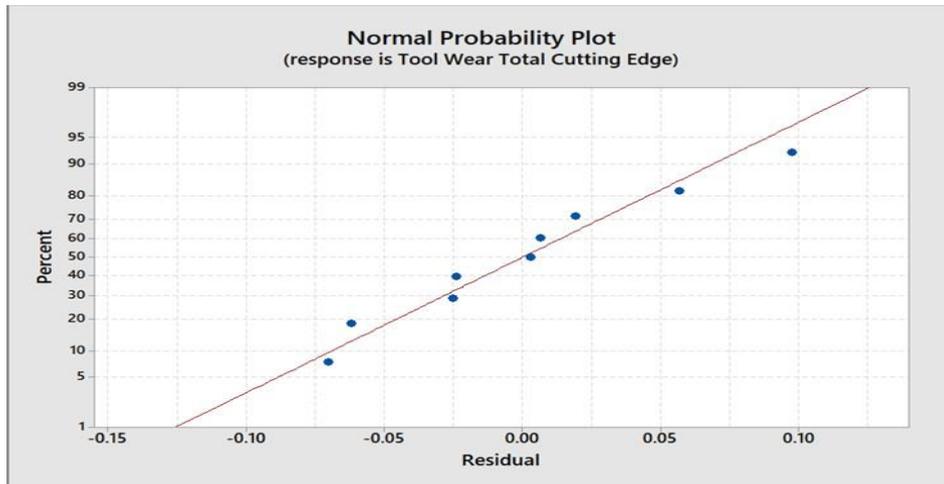


Fig. 5 Normal Probability Plot for Tool Wear Total Cutting Edge

### 3.2.3 Optimization for Minimizing Tool Wear Total Cutting Edge Length

The desire function technique together with linear regression Figure 5 is implemented to minimize tool wear total cutting edge length by using the Taguchi Method. The best cutting conditions for the optimization are found via the use of Minitab-18 statistical software to create a main effects plot for S/N ratios and mean data means, as shown in Figure 6. It illustrates how surface roughness varies with different process parameters, specifically cutting speed, feed rate, and depth of cut.

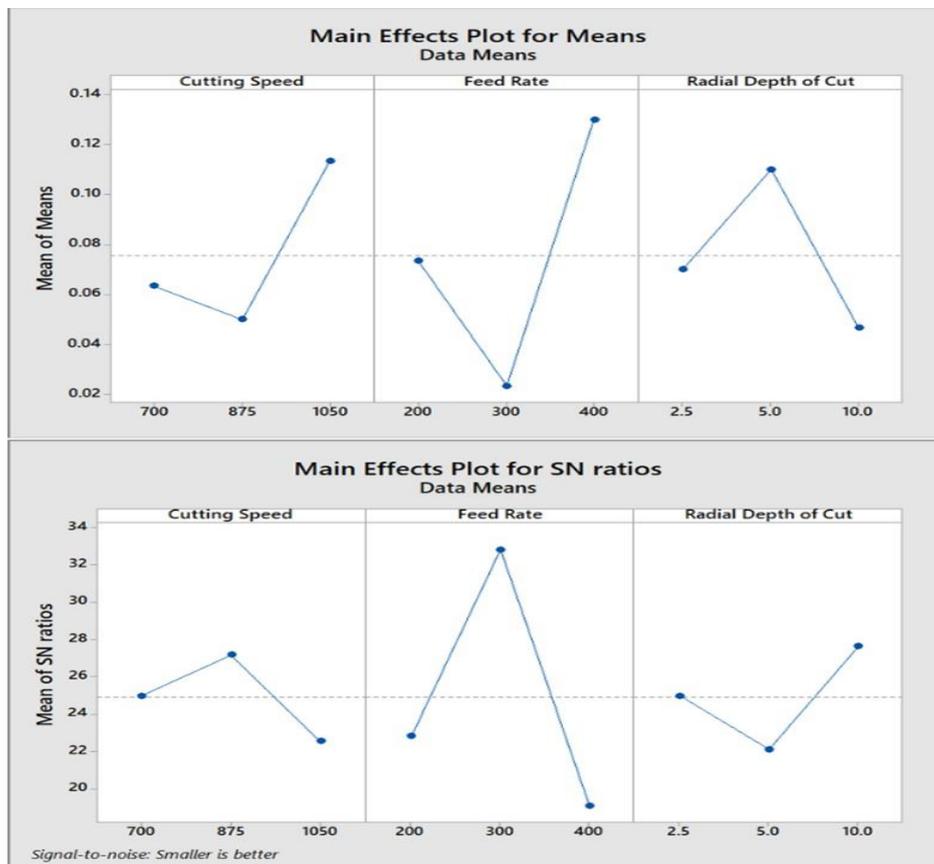


Fig. 6 Main Effects Plot for Means and S/N Ratios of Tool Wear Total Cutting Edge

The Taguchi technique was applied to find the ideal parametric combination for attaining the minimum tool wear total cutting edge length. Factor Cutting Speed at level 2 = 875 rpm (S/N = 27.17 dB, mean = 0.05000 mmdB), Factor Feed Rate at level 2 = 300 mm/min (S/N = 32.81 dB, mean = 0.02333 mmdB) and Factor Radial Depth of Cut at level 3 = 10 mm (S/N = 27.62 dB, mean = 0.04667 mmdB) were found to be the ideal combination, as shown in Figure 5 and Figure 6. The anticipated ideal combination for material removal rate was (Cutting Speed 2 - Feed Rate 2 - Radial Depth of Cut 3).

#### 4. Conclusion

The results from the milling parameters, which are cutting speed, feed rate, and radial depth of cut for tool wear total cutting edge length, have been carried out. According to ANOVA, the parameter that contributed the most for the end mill tool wear is feed rate. The parameters that result in the optimum tool wear total cutting edge length are (Cutting Speed 2 - Feed Rate 2 - Radial Depth of Cut 3), where Cutting Speed = 875rpm, Feed Rate = 300mm/min and Radial Depth of Cut = 10mm. From the statistical analysis, the highest level of significance for responses is recorded by feed rate parameters with 51.13%, while the R-sq value, which is 0.3088, indicates it is not strong enough to indicate high importance for the project model.

Recommendations for the study are, firstly, measuring the flank wear of the end mill instead of the total cutting-edge length is suggested. This adjustment is proposed based on the rationale that flank wear provides a more detailed indication of wear during milling. Secondly, utilising an end mill with a superior surface finish is recommended before the milling process. This step is advised to ensure the measurement of wear after milling with a higher degree of accuracy. Additionally, the application of greater magnification is encouraged to obtain more precise and detailed results. This adjustment aims to enhance the overall accuracy of the findings. Lastly, using steel with high hardness in the experimentation process is advised.

#### Acknowledgement

The authors would like to thank the Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, for their support in conducting the research.

#### Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

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