Surface roughness analysis of high speed milling in grooving

D C Chen* and T W Chen

Department of Industrial Education and Technology, National Changhua University of Education, Changhua 500, Taiwan
*Email: dcchen@cc.ncue.edu.tw

Abstract. High-speed milling is a machining method with a low cutting depth, high feed rate, high cutting speed and high spindle speed. It also has the advantages of small thermal deformation, low cutting force resistance, and low tool wear. In this experiment, the cutting of S45C medium carbon steel was tested. This study used four factors in Taguchi’s experimental design regulations, and each factor used three level configurations. An L9 (3^4) orthogonal table was used to configure the factors and levels. In this study, experiments were conducted on CNC machine tools to explore the difference in the surface roughness of a work piece after cutting with different cutting parameters. It was found that high-speed cutting could indeed obtain quite excellent surfaces. After the experiment, the Taguchi method was analyzed and the results were obtained under different cutting parameters. The experiment is to use milling parameters as variables to analyze the surface roughness, and then the results were analyzed to derive the relationship between the milling parameters and surface roughness. When the feed per edge of the end mill was larger and the number of spindle revolutions was slower, the surface roughness value was larger. The process parameter combination with the best surface quality was 0.1 mm/tooth per edge and a cutting speed of 550 m/min. The best surface roughness of the work piece could be obtained under the combination of a cutting depth of 0.2 mm and a spindle speed 6500 rpm.

1. Introduction
Since the beginning of 2020, most countries around the world have encountered the invasion of COVID-19. This virus has not only caused lock-down policies in various countries but also caused the stagnation of mutual trade between countries. CNC machining companies can only optimize from the manufacturing side and try to find a way out by improving production efficiency, increasing production capacity, and reducing manpower. For machining operations, digital transformation, smart manufacturing, and high-speed precision machining companies are the current development directions. As the most important advanced position manufacturing technology in mold manufacturing, high-speed cutting processing is an advanced position manufacturing technology integrating high efficiency, high quality, and low consumption. A series of problems that have been encountered in conventional cutting have been solved through the application of high-speed cutting. Compared with traditional cutting processes, its cutting speed and feed speed have been improved in stages, and the cutting mechanism has also undergone a fundamental change. Surface integrity is a key property in the functional performance of machined parts and assembled engineering components [1], and surface roughness is an important parameter in mechanical milling machine processing, especially when it is used for relative sliding after precision machining. In the era of high-speed and high-precision CNC machining, excellent CNC operation engineers must understand the characteristics of these beautiful machines. At the same
time, they must also thoroughly understand the mutual influence and setting of the processing parameters, in order to obtain an optimized cutting workpiece. This research used the CAD software Mastercam to establish the tool path for CNC milling machine grooving and changed the cutting parameters through the software’s parameter setting function. As the flank wear is different between the cutting tools used for normal speed cutting and those used for high-speed cutting processes, and because an additional rubbing or plowing force on the wear land could be formed due to the cutting tool flank wear [2], the resultant cutting force direction, which includes the effect of the force on the cutting tool flank face, could differ between the normal and high cutting speed processes and cause different amounts of surface roughness. The cutting parameters in this research included the tool cutting speed, tool feed rate, tool cutting depth, feed engagement tooth, and there were four main parameters, such as the feed rate of each cutting edge of the tool. Each cutting parameter was designed in three levels in the experimental design. Cutting tests were carried out, and the test results were used to predict the best surface roughness through a formula.

2. Methodology
In this study, CNC milling was used, and Mastercam was used as the CAD/CAM software. The main function of the software was to generate processing paths and processing programs, and different cutting modes could be designed through the software. In order to determine the measurement accuracy of the machine tool measurement system, a standard rod was used to test the accuracy of the measurement instrument before the cutting experiment. The surface roughness after cutting was recorded after each cut. The cutting experiment was fully open at equal depths according to the slot cutting method (Figure 2). The cutting tool was a 10 mm end mill, the axial depth of cut was set as 0.1 to 0.3 mm, the increment was 0.1 mm, the spindle speed was from 6500 to 7500 rpm, and the feed rate was 0.05, 0.07, and 0.09 mm per blade. After finishing the cutting, a surface profile measuring instrument made by Mitutoyo was used to measure the machined surface of the workpiece to obtain the roughness of the machined surface under different cutting speed and cutting depth conditions.

2.1. Cutting material for experiment
The cutting material used in the experiment was S45C steel, and the material size was 75 mm * 50 mm. The cutting material used in this research was designed with a total cutting depth of 4 mm, and a 50 mm*10 mm grooving was reserved in the middle of the material. The carbon content of steel exploration materials will directly reflect the hardness of the material. When choosing the mold materials, in order to maintain good mechanical properties, the engineers will choose materials above medium carbon steel. Therefore, this study used medium carbon steel materials to perform the cutting test.

2.2. Machine tools and cutting tools
All the cutting experiments were performed in a YCM-FV56A (Taiwan) CNC machining center (Figure 1) with a continuously variable speed ranging from 6500 to 7500 rpm. The cutting tool was a SKH-Co Nachi end mill with a diameter of 10 mm (the first back angle was 8°, and the second back angle was 15°). This study considered that the wear of the edge of the end mill will directly affect the surface roughness value. The most characteristic feature of an end-milled surface is the tool marks generated between the cusp lines in the feed direction. The generation of tool marks is affected by the geometry of the cutting tool and by the machining parameters. Theoretically, the frequency with which tool marks are generated is related to the feed per tooth, tool deflection, and machining vibrations. If the cutting conditions are not optimal or if the tool is not sharp enough, this can be reflected on the generated surface texture, and the tool marks will not be uniformly distributed in the feed direction [3]. Thus, in this experiment, every time the cutting parameters were changed, a new end mill was used for cutting, so as to prevent wear on the edge and affect the surface roughness value. The cutting process is shown in Figure 2.
2.3. Taguchi method

The Taguchi method is a powerful design used in various engineering analyses to identify significant factors and optimum conditions while reducing the number of experiments and minimizing the effects of uncontrolled factors. The Taguchi method is a powerful design used in various engineering analyses to identify significant factors and optimum conditions while reducing the number of experiments and minimizing the effects of uncontrolled factors [4]. In addition, the use of few trial numbers to obtain the effects of the process parameters on quality characteristics and their optimum levels has easily increased its popularity. This method uses the special design of orthogonal arrays to learn the whole parameter space using a small number of experiments. The Taguchi method employs a signal-to-noise (S/N) ratio to measure the present variation. Also, in the calculation procedure, the effect of different control factors and their interactions is assumed. In Taguchi designs, a measure of robustness is used to identify control factors that reduce variability in a product or process by minimizing the effects of uncontrollable factors [5]. The Taguchi method focuses on the use of statistical methods to optimize design parameters and improve product quality. An orthogonal array is a statistical design experiment tool that reduces the number of tests required, reduces costs, and reduces the time needed for experiments. The objective function of the Taguchi method is the estimate of the S/N ratio. However, this method is mainly applicable to single-objective optimization problems. There are 3 Signal-to-Noise ratios; (1) SMALLER-THE-BETTER: \( n = -10 \log_{10} \left( \frac{1}{n} \sum_{i=1}^{n} y^2_i \right) \) This is usually chosen for all undesirable characteristics like "defects" etc for which the ideal value is zero. Also, when an ideal value is finite and its maximum or minimum value is defined then the difference between measured data and ideal value is expected to be as small as possible. The generic form of S/N ratio then becomes, \( n = -10 \log_{10} \left( \frac{1}{n} \sum \{ \text{measured} - \text{ideal} \} \right) \) (2) LARGER-THE-BETTER: \( n = -10 \log_{10} \left( \frac{1}{n} \sum \left( \frac{1}{\text{measured}} \right)^2 \right) \) This case has been converted to SMALLER-THE-BETTER by taking the reciprocals of measured data and then taking the S/N ratio as in the smaller-the-better case.(3) NOMINAL-THE-BEST: \( n = 10 \log_{10} \left( \frac{\text{mean}}{\text{variance}} \right) \)This case arises when a specified value is MOST desired, meaning that neither a smaller nor a larger value is desirable. Examples are; (i) most parts in mechanical fittings have dimensions which are nominal-the-best type. (ii) Ratios of chemicals or mixtures are nominally the best type. The S/N calculation formula for “lower is better” is [6,7].

\[
S/N = -10 \log_{10} \left( \frac{1}{n} \sum_{i=1}^{n} y^2_i \right)
\]  

2.4. Cutting formula

This research is an experiment to measure the surface roughness of tools with different cutting parameters after cutting. According to the cutting formula" Cutting speed is directly related to tool speed and tool diameter during cutting". For rough machining, tool life and metal removal volume are the primary evaluation indicators and cutting parameters should be prioritized, especially cutting speed and feed per tooth. In finish machining, workpiece surface roughness is the primary evaluation indicator.
Besides the selection of cutting parameters, the design and grinding of endmill are critical factors. In the formula 2, \( V \) represents the cutting speed, \( D \) represents the diameter of the milling cutter for cutting, and \( N \) is the spindle speed of the tool during cutting. [8].

\[
V = \frac{\pi DN}{1000}
\]  \hspace{1cm} (2)

From the calculation formula of the milling machine cutting feed, the factors that affect the cutting feed are \( F \): feed (mm/min), \( S \): speed (rpm), \( Z \): number of edges, \( Fe \): feed engagement.

\[
F = S \times Z \times Fe
\]  \hspace{1cm} (3)

3. Experiment procedure

In this study, the Taguchi method was selected so as to use the least number of experiments and reduce the amount of deviation, reduce labor, time and material consumption, realize other experimental cost advantages, determine the optimization of the process parameters, and realize the duality of improvement. Processing quality reduces production costs benefit. The purpose of this research was to change the cutting parameters of the tool through a number of cutting experiments and then record the surface roughness value after each cut. The \( Ra \) value was used in this research, and statistical software and ANOVA were used for data analysis. Anomaly analysis was used to determine significant design factors, while the Taguchi analysis was used to get the \( S/N \) ratio and the \( S/N \) ratio reaction diagram of each design parameter. The \( S/N \) ratio reaction diagram represented the preliminary optimized design. In this research, the Taguchi quality “lower is better” was used to find the best combination of surface roughness that could be obtained in each cutting parameter. The design flow chart of this research is shown in Figure 3, and the measuring process is shown in Figure 4.

![Figure 3. Research Process.](image-url)

![Figure 4. Measuring surface roughness.](image-url)
4. Results and discussions

4.1. Experiment results

The experiment factors were as follows: spindle speed (A), feed rate (B), cutting depth (C), and feed engagement (D), and each factor had three levels. The spindle speeds were 6500 rpm, 7000 rpm, and 7500 rpm; the feed rates were 500 mm/min, 550 mm/min, and 600 mm/min; the cutting depths were 0.1 mm, 0.2 mm, and 0.3 mm; and the feed engagement was 0.05 tooth/mm, 0.08 tooth/mm, and 0.1 tooth/mm. A Taguchi L₉(3⁴) orthogonal array experimental design was used in the experiments. The experimental factors are shown in Table 1. This experiment used an L₉ (3⁴) orthogonal array (OA) configured by the Taguchi method to carry out the experiment, as shown in Table 2.

| Factors | Content                  | Level 1 | Level 2 | Level 3 |
|---------|--------------------------|---------|---------|---------|
| A       | Spindle speed.rpm        | 6500    | 7000    | 7500    |
| B       | Feed rate/mm/min         | 500     | 550     | 600     |
| C       | Cutting depth/mm         | 0.1     | 0.2     | 0.3     |
| D       | Feed engagement/tooth/mm | 0.05    | 0.08    | 0.1     |

Table 2. Orthogonal array.

| Exp | A. Spindle speed | B. Feed rate | C. Cutting depth | D. Feed engagement |
|-----|------------------|--------------|------------------|--------------------|
| 1   | 1                | 1            | 1                | 1                  |
| 2   | 1                | 2            | 2                | 2                  |
| 3   | 1                | 3            | 3                | 3                  |
| 4   | 2                | 1            | 2                | 3                  |
| 5   | 2                | 2            | 3                | 1                  |
| 6   | 2                | 3            | 1                | 2                  |
| 7   | 3                | 1            | 3                | 2                  |
| 8   | 3                | 2            | 1                | 3                  |
| 9   | 3                | 3            | 2                | 1                  |

The experimental object of this study was the surface roughness of S45C carbon steel after performing cutting tests with different parameters. Thus, in the analysis results, the surface roughness of S45C carbon steel was the main analysis item. The Ra values in Table 3 indicate the surface roughness data. According to the data shown in Table 4, the corresponding S/N response table and S/N response graph could be derived.

| Spindle speed /rpm | Feed rate mm/min | Cutting depth /mm | Feed engagement/mm | Ra /µm |
|--------------------|------------------|-------------------|--------------------|--------|
| 1                  | 6500             | 0.1               | 0.05              | 0.812  |
| 2                  | 6500             | 0.2               | 0.08              | 0.967  |
| 3                  | 6500             | 0.3               | 0.10              | 0.985  |
| 4                  | 7000             | 0.2               | 0.10              | 0.821  |
| 5                  | 7000             | 0.3               | 0.05              | 0.897  |
| 6                  | 7000             | 0.1               | 0.08              | 0.933  |
| 7                  | 7500             | 0.3               | 0.08              | 0.756  |
| 8                  | 7500             | 0.1               | 0.10              | 0.896  |
| 9                  | 7500             | 0.2               | 0.05              | 0.713  |
Table 4. S/N ratio for cutting wear experiment.

| Exp | A | B | C | D | S/N |
|-----|---|---|---|---|-----|
| 1   | 1 | 1 | 1 | 1 | 3.82|
| 2   | 1 | 2 | 2 | 2 | 3.98|
| 3   | 1 | 3 | 3 | 3 | 3.99|
| 4   | 2 | 1 | 2 | 3 | 3.83|
| 5   | 2 | 2 | 3 | 1 | 3.91|
| 6   | 2 | 3 | 1 | 2 | 3.94|
| 7   | 3 | 1 | 3 | 2 | 3.76|
| 8   | 3 | 2 | 1 | 3 | 3.91|
| 9   | 3 | 3 | 2 | 1 | 3.71|

Table 5 lists the factor response for the surface roughness. According to the principles of the Taguchi method, this study assumed that the highest signal-to-noise ratio would represent the highest product quality. Therefore, Figure 5 reveals the optimal design parameter combination and the corresponding value of each factor.

Table 5. Factor response.

|   | Level 1 | Level 2 | Level 3 | Effects | Rank |
|---|---------|---------|---------|---------|------|
| A | 3.93    | 3.89    | 3.79    | 0.14    | 1    |
| B | 3.81    | 3.93    | 3.88    | 0.12    | 2    |
| C | 3.88    | 3.95    | 3.89    | 0.07    | 4    |
| D | 3.81    | 3.89    | 3.91    | 0.10    | 3    |

Figure 5. S/N response graph of the experiment.
4.2. Analysis of variance

Variance analysis was used to evaluate the influence of the experimental factors on the surface roughness through percentage quantification and then make correct judgments and evaluations. Table 6 lists the results of the original data for the analysis of variance. The F value is the amount of variation. It was used to evaluate whether the verification factor was significantly different from the evaluation level. The P value indicates the probability of experimental error. After statistical verification, the F value of the variance reached a significant difference, and a P value \( \leq F \) also proved that the experimental factor had a significant influence on the variables.

| Source          | Squares | df | Mean square | F    | P  |
|-----------------|---------|----|-------------|------|----|
| Between groups  | 0.169   | 1  | 0.169       | 4.02 | 5.12* |
| Intra class     | 0.373   | 9  | 0.0414      |      |     |
| Total           | 0.542   | 10 |             |      |     |

*P<.05

4.3. Predict the best combination

The best combination of cutting parameters can predict the surface roughness of the workpiece to be processed, the prediction result as follows:

\[
R = \bar{R} + (\bar{R}_{A1} - \bar{R}) + (\bar{R}_{B2} - \bar{R}) + (\bar{R}_{C2} - \bar{R}) + (\bar{R}_{D3} - \bar{R})
\]

\[
0.91 + (0.92 - 0.91) + (0.92 - 0.91) + (0.88 - 0.91) + (0.91 - 0.91) = 0.90 \mu m
\]

This research confirmed the best cutting parameters obtained by the Taguchi method (A1, B2, C2, and D3), in order to confirm whether the surface roughness obtained by the best cutting parameters was consistent with the prediction. Therefore, this research once again conducted confirmation experiments on the best combined cutting parameters (0.1 mm/tooth per edge, a cutting speed of 550 m/min, a cutting depth of 0.2 mm, and a spindle speed of 6500 rpm). The surface roughness value obtained after re-cutting and measurement was 0.86 \( \mu m \) the value obtained in the certification experiment is that although it reached the combined predicted value of 0.90 \( \mu m \), it was significantly better than the cutting parameters of any combination of this experiment. Therefore, under the above conditions, the best surface roughness for high-speed machining was 0.90 \( \mu m \). The value obtained in the certification experiment was 0.86 \( \mu m \). Although this did not reach the combined predicted value of 0.90 \( \mu m \), it was significantly better than any combination of cutting parameters. Therefore, under the above conditions, the best surface roughness for high-speed machining was found to be 0.86 \( \mu m \).

5. Conclusion

This article is mainly based on S45C middle carbon steel, using Taguchi experimental design method to plan the experiment, 10 mm diameter end mill and mastercam software to discuss the best surface roughness. Experiment with Taguchi experiment method, obtain the best combination of cutting parameters through the S/N ratio auxiliary table, and conduct the best combination experiment to verify the correctness of the surface roughness experiment. From the analysis results, we can understand the situation of Surface roughness under different cutting parameters. The combination of cutting is explained as follows: the combination of 0.1 mm/tooth per edge, a cutting speed of 550 m/min, a cutting depth of 0.2 mm, and a spindle speed of 6500 rpm could result in the best surface roughness.
Acknowledgments
I am grateful to the Ministry of Science and Technology, Taiwan, for its support and funding for this research; Project Number (MOST 109-2511-H-018-009).

References
[1] Safari H, et al. 2015 Surface Integrity Characterization in High-Speed Dry End Milling of Ti-6Al-4VTitanium Alloy. International Journal of Advanced Manufacturing Technology vol 78 no 1-4, Apr. pp 651–657
[2] Wang J, Huang C Z and Song W G 2003 The effect of tool flank wear on the orthogonal cutting process and its practical implications. J Mater Process Technol. 142(2) pp 338–346
[3] Cuka B, et al. 2018 Vision-Based Surface Roughness Evaluation System for End Milling. International Journal of Computer Integrated Manufacturing vol 31 no 8, Aug. pp 727-738
[4] Phadake M S 1989 Quality Engineering Using Robust Design 013745167-9. Google Scholar
[5] Chiang H L, Yang C B and Hsu C Y 2016 Combining Taguchi Signal-to-Noise Ratio and Grey Relational Analysis into a Multi-Objective Optimal Model for Milling Inconel 718 Superalloy, Journal of the Chinese Society of Mechanical Engineers, 625
[6] Lin C L and Dai H M 2020 Multi-Objective Optimization of Thermal Drilling Process Using TOPSIS with Taguchi Method. International Journal of Uncertainty and Innovation Research, no 3 p 225
[7] Saito Y and Utsunomiya H 1993 Rolling of T-shaped profiled metal strip by calibered central roll method—studies on satellite-mill rolling III, JSTP pp 1015-1021
[8] Taguchi G et al.1989 Quality Engineering in Production Systems, McGraw-Hill, New York, USA