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# Parametric Optimization on Multi-Objective Precision Turning Using Grey Relational Analysis

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**Abstract:** In this study, $L_9(3^4)$ orthogonal array of Taguchi experiment is selected for four parameters (speed, cutting depth, feed rate, tool nose runoff) with three levels in optimizing the multi-objective (surface roughness, tool wear and material removal rate) precision turning on an ECOCA-3807 CNC (Computer Numerical Controlled) lathe. Through the examination of surface roughness ($R_a$), tool wear ratio ($mm^{-2}$) and the calculation of MRR; the multiple objectives are then received. By using Grey Relational Analysis (GRA), the multiple objectives can additionally be integrated and introduced as the S/N (signal to noise) ratio into the Taguchi experiment. The mean effects for S/N ratios are moreover analyzed by MINITAB to achieve the multi-objective turning parameters. Through the verification results, it is shown that both surface roughness and tool wear ratio from present optimum parameters are greatly advanced with minor decrease on the MRR (Material Removal Rate) comparing to those from benchmark parameters. This study not only proposes a novel optimization technique using GRA, but also contributes the satisfactory solution for multiple CNC turning objectives with profound insight.

**Key words:** Computer numerical controlled, Taguchi method, multiple quality, relational rating

## INTRODUCTION

Surface roughness, tool life and cutting force are commonly considered as manufacturing goals (Davim and Conceicao Antonio, 2001) for turning operations in many of the existing researches. It is also recognized that lighter cutting force often results to better surface roughness and tool life. This is why smaller cutting conditions conclude toward to be optimum (Lin *et al*., 2001). As the flexibility and adaptability needs increased, the stability of modern CNC machines is now designed robust. Since the productivity concern becomes more critical than the cutting force in the industry, the Material Removal Rate (MRR) is more to be concerned than the cutting force.

The machining process on a CNC (Computer Numerical Controlled) lathe is programmed by speed, feed rate and cutting depth, which are frequently determined based on the job shop experiences. However, the machine performance and the product characteristics are not guaranteed to be acceptable. Therefore, the optimum turning conditions have to be accomplished. It is mentioned that the tool nose run-off will affect the performance of the machining process (Yeh, 1994). To reduce the costly and time-consuming experiments, this study employs the tool wear ratio (tool wear length per unit material removal volume) instead of the tool life to demonstrate the tool wear status of turning under specific parameter combination.

Among the existing parametric optimization researches on turning conditions, Lin *et al.* (2001) have constructed simulation models for surface roughness and cutting forces using convergence network. Davim *et al.* (2001) have developed mathematical models to express cutting force as functions of surface roughness and tool life and then optimize the turning parameters by using GA (genetic algorithm). Nevertheless, these are regarded as computing simulations and the applicability to real world industry is still uncertain. Parameter optimization for attribute is a hard-solving issue because of the interactions between parameters. Problems related to the enhancement of product quality and production efficiency can always be related to the optimization procedures. Taguchi method, an experimental design method, has been widely applied to many industries. It can not only optimize quality characteristics through the setting of design parameters, but also reduce the sensitivity of the system performance to sources of variation (Huh *et al*., 2003; Kim *et al*., 2003). The Taguchi method adopts a set of orthogonal arrays to investigate the effect of parameters on specific quality characteristics to decide the optimum parameter combination. These kinds of arrays use a small number of experimental runs to analyze the quality effects of parameters as well as the optimum combination of parameters.

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With all the viewpoints, this study proposes an optimization approach using orthogonal array and GRA (Grey Relational Analysis), a multi-objective integration technique, to optimize precision CNC turning conditions. Therefore, the optimum multi-objective cutting parameters can then be achieved through the analysis of factor responses in the Taguchi experiment. This study definitely contributes the optimum solution of compromising technique for multiple precision CNC turning objectives with profound insight.

## MATERIALS AND METHODS

The study proposed in this research was conducted in 2007. In this study, the multi-objective integration and parameter optimization technique for CNC turning operations are proposed using GRA (Grey Relational Analysis) and Taguchi method (Palanikumar, 2008; Ross, 1998), respectively.

**Integration of multiple objectives:** The Grey theory has been first developed since 1982 (Lin and Lin, 2002) to construct the system uncertainty for relation analysis, modeling, forecasting, decision and control. The GRA (Grey Relational Analysis) is mainly utilized in finding the major relations in the system (Lin and Lin, 2001) to assess the alternatives before multiple-attribute decision making. GRA considers simultaneously the overall relational rating regarding each alternative and also selects the most valuable degree as the best alternative. The computational steps of GRA can be expressed as:

**Step 1:** Compute the accumulated probability for each ranking category

**Step 2:** Formulate the grey relation on each ranking category parameter with accumulated probability

$$x_i*(k) = \frac{x_i(k) - x^{min}(k)}{x^{max}(k) - x^{min}(k)} \tag{1}$$

Here, $x_i$ is the number of the ith experiment for the kth ranking category parameter, $x^{max}(k)$ denotes the maximum number of the kth ranking category parameter, $x^{max}(k)$ represents the minimum number of the kth ranking category parameter and $x_i$ expresses the gray formulation value of the kth ranking category parameter at the ith experiment.

**Step 3:** Compute the grey relational coefficient for each experiment combination

When the objective evaluation is divided into n ranking categories, the maximum grey formulation for each ranking category (equals to 1) is utilized as the reference serial. We then have

$$\gamma\left(x_0^*(k), x_i^*(k)\right) = \frac{\min_i \min_k \left|x_0^*(k)-x_i^*(k)\right| + \varsigma \max_i \max_k \left|x_0^*(k)-x_i^*(k)\right|}{\left|x_0^*(k)-x_i^*(k)\right| + \varsigma \max_i \max_k \left|x_0^*(k)-x_i^*(k)\right|} \tag{2}$$

Here, $\gamma(x_0*(k), x_i*(k)$ is the grey relational coefficient for comparative serial from the accumulated probability of n-1 ranking categories between the ith experiment and reference serial and $x_0*(k)$ describes the grey formulation value of reference serial at the kth ranking category parameter.

**Step 4:** Determine the overall relational rating for each experiment combination

$$\gamma\left(x_0*, x_i*\right) = \frac{1}{n-1}\sum_{k=1}^{n-1}\gamma\left(x_0*(k), x_i*(k)\right) \tag{3}$$

Here, $\gamma(x_0*, x_i*)$ states the overall relational rating for comparative serial from the accumulated probability of n-1 ranking categories between the ith experiment and reference serial.

**Taguchi method:** The Taguchi method is a robust design method technique (Palanikumar, 2008; Ross, 1998), which provides a simple way to design an efficient and cost effective experiment. In order to efficiently reduce the numbers of conventional experimental tasks, the orthogonal array (Chang, 2000; Wei *et al*., 2002) by using design parameters (control factors) in column and standard quantities (levels) in row is proposed and further adopted. The performance measure, signal to noise ratio (S/N) (Park *et al*., 2005) proposed by Taguchi is used to obtain the optimum parameter combinations. The larger S/N means the relation to the quality will become better. The lower quality characteristic will be regarded as a better result when considering the smaller-the-best quality. The related S/N ratio is defined as:

$$S/N = -10\left(\log\sum_{i=1}^{n}\frac{y_i^2}{n}\right)\ \text{(dB)} \tag{4}$$

where, n is the number of experiments for each experimental set and $y_i$ expresses the quality characteristic at the ith experiment. On the contrary, the larger quality characteristic will have better result t when considering the larger the best quality, therefore, by taking the inverse of quality characteristic into Eq. (1), the related S/N ratio can also be deduced and shown in Eq. (2).

$$S/N = -10\left(\log\sum_{i=1}^{n}\frac{1/y_i^2}{n}\right)\ (\text{dB}) \qquad (5)$$

In this study, the overall relational rating using GRA for multiple precision CNC machining objectives is introduced to the Taguchi experiment as the S/N ratio. Therefore, it is judged as the quality of larger the best. In addition to the S/N ratio, a statistical analysis of variance (ANOVA) (Wu and Chree, 2002) can be employed to indicate the impact of process parameters. In this way, the optimal levels of process parameters can be estimated.

## RESEARCH DESIGN

The precision diameter turning operation of S45C (φ45×250 mm) work piece on an ECOCA-3807 CNC lathe is arranged for the research. The TOSHIBA WTJNR2020K16 tool holder with MITSUBISHI NX2525 insert is utilized as the cutting tool. The design is shown as follows.

**Experimental setup:** The surface roughness ($R_a$) of machined work pieces are measured on the MITSUTOYO SURFTEST. The tool wearing length VB2(mm) in Fig. 1 is scaled on the 3D SONY COLOR VIDEO electronic camera. The tool wearing length is then divided by the volume of material removed as the tool wear ration ($mm^{-2}$), which is utilized as the indicator of tool wear in this study. And, the MRR($mm^3\ min^{-1}$) is calculated using the following Eq.

$$MRR = 1000\ fdv \qquad (6)$$

In Eq. (6); f (mm per revolution) denotes the feed rate, d (mm) describes the cutting depth and v($m\ min^{-1}$) presents the surface speed of the turning operation.

**Construction of orthogonal array:** In this study, the four turning parameters (cutting depth, feed rate, speed and tool nose runoff) with three different levels (Table 1) are experimentally constructed for the machining operation. In Table 1, the three levels of cutting depth, feed rate and speed are identified from the machining handbook suggested by the tool manufacturer. The tool nose runoff is positioned by using different shims located under the tool holder and determined by measuring the tip after face turned the work piece. When the tool nose is set approximately 0.1 mm higher (lower) than the center of the work piece, it is regard as Level 1 (Level 3). When the tool nose is set within ±0.03 mm, it is considered as Level 2. The orthogonal array is then selected to perform the nine sets of machining experiments. The parameter levels for the experiments are illustrated in Table 2.

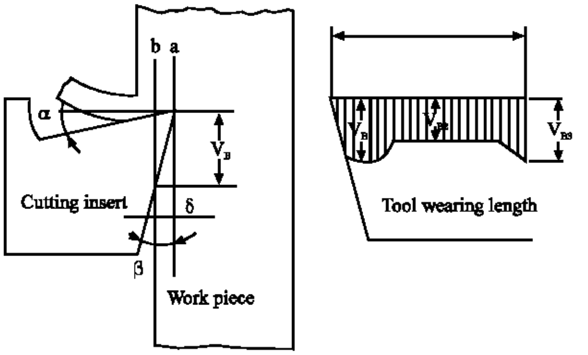

Fig. 1: Tool wear length

Table 1: Parameters and levels

| | Level | | |
|---|---|---|---|
| Parameters | 1 | 2 | 3 |
| A: Speed (m $min^{-1}$) | 150.00 | 200.00 | 250.0 |
| B: Cutting depth (mm) | 0.50 | 1.00 | 1.5 |
| C: Feed rate (mm $rev^{-1}$) | 0.02 | 0.06 | 0.1 |
| D: Tool nose run off (mm) | 0.10 | ±0.03 | -0.1 |

Table 2: Orthogonal array

| | Parameter | | | |
|---|---|---|---|---|
| Experiments | A (speed) | B (cutting depth) | C (feed rate) | D (tool nose runoff) |
| 1 | Level 1 | Level 1 | Level 1 | Level 1 |
| 2 | Level 1 | Level 2 | Level 2 | Level 2 |
| 3 | Level 1 | Level 3 | Level 3 | Level 3 |
| 4 | Level 2 | Level 1 | Level 2 | Level 3 |
| 5 | Level 2 | Level 2 | Level 3 | Level 1 |
| 6 | Level 2 | Level 3 | Level 1 | Level 2 |
| 7 | Level 3 | Level 1 | Level 3 | Level 2 |
| 8 | Level 3 | Level 2 | Level 1 | Level 3 |
| 9 | Level 3 | Level 3 | Level 2 | Level 1 |

## RESULTS AND DISCUSSION

In this study, each work piece is diameter turned 150 mm in length from the face with three passes using a brand new cutting edge of the insert. The experimental results are described as follows.

**Multi-objective optimization:** By considering the parameter combinations of the nine sets of experiment based on the $L_9(3^4)$ orthogonal array, the machining objectives are determined and shown as Table 3. With the machined results based on the orthogonal array, the overall relational rating for each experiment combination by using GRA can then be achieved and shown in Table 4.

Table 3: Machined results

| | Objective | | |
|---|---|---|---|
| Experiment | Surface roughness $R_a$(μm) | Tool wear ($mm^{-2}$) | MRR ($mm^3$ $min^{-1}$) |
| 1 | 0.6231 | 6.67E-07 | 0.015 |
| 2 | 0.7300 | 4.72E-07 | 0.090 |
| 3 | 0.7100 | 3.67E-07 | 0.225 |
| 4 | 0.6300 | 8.46E-07 | 0.060 |
| 5 | 0.7866 | 5.98 E-07 | 0.200 |
| 6 | 0.5348 | 3.43E-07 | 0.060 |
| 7 | 0.7066 | 8.46E-07 | 0.125 |
| 8 | 0.6466 | 4.13E-07 | 0.050 |
| 9 | 0.5100 | 2.91E-07 | 0.225 |

Table 4: Overall relational rating

| Experiment | Relational rating |
|---|---|
| 1 | 0.676278946 |
| 2 | 0.649257286 |
| 3 | 0.554769158 |
| 4 | 0.605486389 |
| 5 | 0.558384398 |
| 6 | 0.680609873 |
| 7 | 0.498995255 |
| 8 | 0.603089117 |
| 9 | 0.548268017 |

Table 5: Result of factor responses

| | Parameter | | | |
|---|---|---|---|---|
| | A | B | C | D |
| Level | | | | |
| 1 | 0.5419 | 0.5050 | 0.6603 | 0.5201 |
| 2 | 0.5271 | 0.5279 | 0.5482 | 0.5620 |
| 3 | 0.5479 | 0.5840 | 0.4085 | 0.5348 |
| Rage | 0.0209 | 0.0790 | 0.2518 | 0.0419 |

Table 6: Confirmation results

| | Surface roughness (μm) | Tool wear ratio ($mm^{-2}$) | MRR ($mm^3$ $min^{-1}$) | Relational rating |
|---|---|---|---|---|
| Optimum Quality | 0.4133 | 3.38E-07 | 0.0075 | 0.72566 |
| Benchmark Quality | 0.9233 | 4.38E-07 | 0.0120 | 0.59654 |

Introducing the relational rating as the signal to noise ratio (S/N) of multiple machining objectives for larger-the-best expectation, the results of factor responses are calculated and listed in Table 5. The mean effects for S/N ratios are then drawn by MINITAB 14. Therefore, the optimum multi-objective turning parameters are found to be A3 (250 m $min^{-1}$), B3 (1.5 mm), C1 (0.02 mm $rev^{-1}$), D2 (±0.03 mm).

**Optimality confirmations:** To verify the optimum result achieved by present proposed optimization technique, the machining operations under both optimum parameters and benchmark parameters (A2B2C2D2), which are often introduced into the confirmation experiment in many of the studies (Tosun and Ozler, 2004; Lin and Lin, 2006) for comparison to the optimum parameters, are performed on the CNC lathe. The machined results are concluded and listed in Table 6. From Table 6, it is observed that the MRR under optimum parameters is decreasing about 37.5%. However, the surface roughness and tool wear ratio are greatly improved by 55.23 and 22.83%, respectively. And, the overall relational rating is also improved by 21.64%.

## CONCLUSION

In this study, the Taguchi optimization using GRA was proposed and applied to achieve the optimum process parameters of precision CNC turning under the considerations of multiple objectives. A confirmation experiment within the optimum parameters was conducted to indicate the effectiveness of the proposed optimization method. Through the confirmation test, the experimental results validate the effectiveness that most qualities can be greatly advanced from our optimum technique with minor negotiation.

Parametric optimization is a hard-solving matter because of the interactions between parameters. This study not only proposes an optimization approach using orthogonal array and GRA, but also contributes the satisfactory technique for improving the multiple machining performances in precision CNC turning with profound insight.

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