Multi-response Optimization of Surface Roughness
Roundness and MRR in Precision Turn-Boring of
15-5PH Stainless Steel Using Taguchi-Grey Approach

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Abstract: The present study propose an innovative turn-boring operation method and
focuses on finding optimal turn-boring process parameters for 15-5PH Stainless steel by
considering multiple performance characteristics using Taguchi orthogonal array with the
grey relational analysis, the effect of machining variables such as concentration of cutting
fluid, temperature of cutting fluid, feed rate, depth of cut and cutting speed are optimized
with considerations of multiple performance characteristics namely surface roughness,
roundness error and material removal rate, the optimal values were found out from the Grey
relational grade. The result of the Analysis of Variances (ANOVA) is shown that the most
significant factor is cutting speed, followed by feed rate, concentration of cutting fluid,
radial depth of cut and temperature of cutting fluid. Finally, confirmation tests were carried
out to make a comparison between the experimental results and developed model.
Experimental results have shown that machining performance in the turn-boring process
can be improved effectively through this approach.

Keywords: surface roughness; roundness; MRR; turn-boring; optimization; Taguchi-grey.

1. Introduction

Fine boring is one of the important machining aerospace and automotive parts that have to
be efficient and high accuracy. It is an important task to select cutting parameters for
achieving superior cutting performance. The evolution of boring machining operation
properties using different parameters is a complex phenomenon. There are many factors
such as cutting speed, depth of cut, feed rate, insert material etc affecting the performance
of boring machining operation resulting in different surface quality and
accuracy. Venkatarao et al. [1] studied the effect of various input cutting parameters such as
cutting speed, feed rate, and tool nose radius on tool life in boring for AISI 1040 steel by
analyzing surface roughness, amplitude of work piece vibration and volume of metal removed. Venkatarao et al. [2] using an artificial neural network to predict the cutting tool wear, surface roughness and vibration of the work piece in boring of AISI 316 steel. Chun et al. [3] using the response surface methodology to study the effect of the overhang, feed rate, and the depth of cut on machining errors in boring for AISI4140 steel. They found the depth of cut is the most significant parameters affecting the dimensional accuracy.

15-5 PH stainless steels are widely used as structural components in applications such as aircraft and power plants industries [4]. It is show excellent mechanical properties, high strength and hardness, good corrosion resistance and low distortion. But, their machinability is more difficult compared to other alloy steels due to low thermal conductivity, high built-up edge (BUE) formation tendency and high deformation hardening.

With the development of technology in aerospace and automobile industry, conventional machining operations can be not enough to satisfy machining quality, productivity and cost demands. To improve processing quality and varieties of metal compound machining methods has been developed. At this point, an innovative process such as turn-milling is an effective way of machine difficult-to-cut materials as a kind of compound machining. Schulz [5] proposed two different turn-milling operations, namely coaxial and orthogonal, and carried out experimental trials to identify cutting conditions (i.e. feed, speeds, depth of cut) that result in a good surface. He has further concluded that short chips are formed by intermittent cutting process. Choudhury and Mangrulkar [6] carried out a series of orthogonal turn-milling experiments and states that surface finish quality obtained by orthogonal turn-milling will be about 10 times better than those obtained by conventional turning.

Base on turn-milling method idea, we also proposed a new innovative turn-boring technology of both the boring tool cutter and workpiece rotation simultaneously. Due to the direction of rotation of the tool and the workpiece is reversed, resultant from intermittent cuts and chip breaking. It keeps low thermal stresses, lowers cutting forces and has useful material removal rates. It also can offer increased productivity for difficult-to-machine materials. So far, this compound processing machining method has not yet seen any study reports.

Even though a very few research works have been carried out to study the influence of boring parameters on different quality. However, CNC turn-boring have not seen the report, it is very necessary to establish optimal parametric combination with the intention of obtaining improved machined surface, accuracy and material removal rates. This study focused on the optimal turn-boring parameters considering the multiple qualities characteristics such as surface roughness, roundness and material remove rate using Taguchi based the Grey Relational Analysis (GRA). The grey relation analysis theory proposed by Deng [7] was used for solving the complex interrelationship among the
multi-objective optimization. It’s is an effective approach to solve the multi-objective optimization. Recently, some researchers have effectively used this method for solving the intricate interrelationships between the multiple objectives in engineering manufacture with multiple responses. Kuram and Ozcelik [8] employed the Taguchi method and the Grey Relational Analysis to multi-optimize with multiple response outputs in the micro-milling. They studied the effects of spindle speed, feed per tooth and depth of cut on tool wear, force, and surface roughness. Yang et al. [9] applied the Taguchi method and the GRA to optimize the milling parameters such as the cutting speed, the feed rate, and the depth of cut for simultaneous optimization of the energy, production rate and cutting quality. Dabade [10] conducted the multi-objective process optimization with Grey Relational Analysis to develop the surface integrity in turning of Al/SiCp metal matrix composites. Hwang et al. [10] investigated and optimized the high speed end milling of SKD61 Tool Steel using Taguchi methods with grey relational analysis. Recently, this method attracts more and more widely applied on mechanical machining and tribological engineering, including drilling [12-14], turning [15-16], milling [17-18], wire electrical discharge machining [19-20], and tribology [21].

As mentioned above, The GRA is an effective approach to solve the multi-objective optimization. Therefore, this study applied a Taguchi L27 orthogonal array to plan the experiments. The experimental design was organized for five parameters including cutting fluid concentration, cutting fluid temperature, feed rate, depth of cut and relative cutting speed of turn-boring with three levels for each factor. This study presented the multi-response optimization of turn-boring parameters to simultaneously minimize the surface roughness, roundness and maximize material remove rate using Taguchi based GRA in turn-boring of 15-5 PH stainless steel.

2. Experimental procedure

Turn-boring experiments were conducted on YAMAZAKI MAZAK INTEGREX 300-IV multi-tasking machine. The test materials were chosen as 15-5PH stainless steel. Its chemical composition and mechanical properties are shown in Tables 1 and 2, respectively. The schematic diagram of the experimental set-up is illustrated in Fig. 1. Dimension of the workpiece was a length of 30mm outer diameter of 60mm and inner diameter of 32mm is shown in Fig. 2. The experimental conditions used to refer to a turn-boring operation are summarized in Tables 3. The cutting fluid properties are shown in table 4. Turn-boring parameters and their levels as showed in Table 5. Taguchi’s L27 orthogonal arrays are given in Table 6. The machining parameters are concentration of cutting fluid , temperature of cutting fluid , feed rate, depth of cut and cutting speed and the output response is surface roughness (Ra), roundness error (Er) and material removal rate (MRR), the surface roughness Ra is measured with surface roughness tester (MITUTOYO, MODEL SJ210),
the roundness is measured with Coordinate Measuring Machine (DEA GLOBAL Silver SF 12.15.10). The material removal rate is calculated by using Eq. (1), as showed in Fig 3.

\[
MRR = \frac{\pi a_p f_r n(D_2^2 - D_1^2)}{4}
\]  

(1)

where \( n = 1000V_c/\pi D_2 \), MRR: Material Removal Rate. \( a_p \) is Axial length of cut. \( D_2 \) is Finished Diameter. \( D_1 \) is Initial diameter. \( n \) is machine speed in revolutions/minute. \( f_r \) is machine feed rate.

Table 1. Chemical composition of the 15-5PH alloy (at%)

| %  | Cr | Ni | Cu | Mn | Si | Mo | Nb | C  | P  | S  | Fe   |
|----|----|----|----|----|----|----|----|----|----|----|------|
| Min| 14 | 3.5| 2.5| 0  | 0  | 0  | 0.15| 0  | 0  | 0  | Bal  |
| Max| 15.5| 5.5| 4.5| 1  | 1  | 0.5| 0.45| 0.07| 0.05| 0.026| Bal  |

Table 2. Workpiece material properties

|                  |                      |
|------------------|----------------------|
| Hardness (HRC)   | 35HRC                |
| Melting point (˚C)| 550                  |
| Ultimate textile strength (Mpa) | 1150±50             |
| Yield serength (Mpa) | 1050±50              |
| Impact-toughness (J/cm²) | Longitudinal 171-180 |
| Modulus of elasticity (Mpa) | 196000              |

Table 3. Experimental conditions.

|                  |                      |
|------------------|----------------------|
| Workpiece materials | 15-5PH Stainless steel |
| Equipment        | INTEGREX300-IV ST    |
| Process          | Horizontal internal Boring |
| Tool Bar type    | SANDVIK CoroBore®825 -23TC06-C3 |
| Boring Insert type | CoroTurn® 107        |
| Boring Insert geometry | Triangularity         |
| Boring Insert material | Tungsten steel       |
| Boring Insert coating | TiAlN                |
| Lubrication coolant supply | B-Cool 675         |

Table 4. Cutting fluid properties

|                  |                      |
|------------------|----------------------|
| Manufacturer     | Blaser Swisslube     |
| Trade name       | B-Cool 675           |
| pH-value         | 8.5 - 9.2 @ 50 g/l H2O (DIN 51369) |
| Density at 20°C  | 1.02 g/cm³ (DIN 51757) |
| Viscosity at 40°C| 60 mm²/s (ISO 3104)  |
| Flash point (˚C) | 143°C (ISO 2592)     |
| Refractive index | 1.430                |
Table 5. Turn-boring parameters and their levels.

| Symbol | Control parameters               | unit     | Level 1 | Level 2 | Level 3 |
|--------|----------------------------------|----------|---------|---------|---------|
| A      | Concentration of Cutting fluid   | %        | 15      | 20      | 25      |
| B      | Temperature of Cutting fluid     | °C       | 20      | 22      | 24      |
| C      | Feed rate                        | mm/rev   | 0.170   | 0.250   | 0.330   |
| D      | Radial depth of cut              | mm       | 0.050   | 0.100   | 0.150   |
| E      | Cutting speed                     | m/min    | 16      | 23      | 30      |
Table 6 Experiment design and real value.

| No. | A | B | C | D | E | Concentration of cutting fluid | Temperature of Cutting fluid | Feed rate | Radial depth of cut | Cutting speed |
|-----|---|---|---|---|---|-------------------------------|-----------------------------|-----------|-------------------|--------------|
| 1   | 1 | 1 | 2 | 3 | 2 | 15                            | 22                          | 0.33      | 0.10              | 16           |
| 2   | 1 | 1 | 2 | 3 | 3 | 15                            | 22                          | 0.33      | 0.15              | 23           |
| 3   | 1 | 1 | 2 | 3 | 1 | 15                            | 22                          | 0.33      | 0.05              | 30           |
| 4   | 1 | 3 | 1 | 2 | 2 | 15                            | 24                          | 0.17      | 0.10              | 23           |
| 5   | 1 | 3 | 1 | 3 | 3 | 15                            | 24                          | 0.17      | 0.15              | 30           |
| 6   | 1 | 3 | 1 | 1 | 1 | 15                            | 24                          | 0.17      | 0.05              | 16           |
| 7   | 1 | 1 | 2 | 2 | 3 | 15                            | 20                          | 0.25      | 0.10              | 30           |
| 8   | 1 | 1 | 2 | 3 | 1 | 15                            | 20                          | 0.25      | 0.15              | 16           |
| 9   | 1 | 1 | 2 | 1 | 2 | 15                            | 20                          | 0.25      | 0.05              | 23           |
| 10  | 2 | 2 | 1 | 3 | 2 | 20                            | 22                          | 0.17      | 0.15              | 23           |
| 11  | 2 | 2 | 1 | 1 | 3 | 20                            | 22                          | 0.17      | 0.05              | 30           |
| 12  | 2 | 2 | 1 | 2 | 1 | 20                            | 22                          | 0.17      | 0.10              | 16           |
| 13  | 2 | 3 | 2 | 3 | 3 | 20                            | 24                          | 0.25      | 0.15              | 30           |
| 14  | 2 | 3 | 2 | 1 | 1 | 20                            | 24                          | 0.25      | 0.05              | 16           |
| 15  | 2 | 3 | 2 | 2 | 2 | 20                            | 24                          | 0.25      | 0.10              | 23           |
| 16  | 2 | 1 | 3 | 3 | 1 | 20                            | 20                          | 0.33      | 0.15              | 16           |
| 17  | 2 | 1 | 3 | 1 | 2 | 20                            | 20                          | 0.33      | 0.05              | 23           |
| 18  | 2 | 1 | 3 | 2 | 3 | 20                            | 20                          | 0.33      | 0.10              | 30           |
| 19  | 3 | 2 | 2 | 1 | 3 | 25                            | 22                          | 0.25      | 0.05              | 30           |
| 20  | 3 | 2 | 2 | 2 | 1 | 25                            | 22                          | 0.25      | 0.10              | 16           |
| 21  | 3 | 2 | 2 | 3 | 2 | 25                            | 22                          | 0.25      | 0.15              | 23           |
| 22  | 3 | 3 | 3 | 1 | 1 | 25                            | 24                          | 0.33      | 0.05              | 16           |
| 23  | 3 | 3 | 3 | 2 | 2 | 25                            | 24                          | 0.33      | 0.10              | 23           |
| 24  | 3 | 3 | 3 | 3 | 3 | 25                            | 24                          | 0.33      | 0.15              | 30           |
| 25  | 3 | 1 | 1 | 1 | 2 | 25                            | 20                          | 0.17      | 0.05              | 23           |
| 26  | 3 | 1 | 1 | 2 | 3 | 25                            | 20                          | 0.17      | 0.10              | 30           |
| 27  | 3 | 1 | 1 | 3 | 1 | 25                            | 20                          | 0.17      | 0.15              | 16           |
3. Results and discussions

Multi-response optimization with Grey relational analysis

Grey relational analysis is a statistical method to analyze the complex multi-response systems. Based on experimental data, the Grey relational analysis is utilized to convert the multi-response optimization into the single objective optimization of the grey relational grade. The aim of this study was to identify the optimal combination of turn-boring parameters that simultaneously minimize surface roughness, roundness and maximize the material removal rate in turn-boring of 15-5PH stainless steel. Steps of grey relational analysis are as follows:

3.1 Grey relational generation

The first step of grey relational analysis is to normalize the experimental data depending on the type of performance response. Ra, Er and MRR are to normalize in the range of zero to one. This is called grey relational normalization. In the present study, as surface roughness and roundness had to be minimized, the smaller-the-better model aims to obtain the minimum quality characteristics. MRR had to be maximized.

For the Lower-the-better criterion, the normalize data can be expressed as

\[
x_i^*(k) = \frac{\text{max}(x_i^k(k)) - (x_i^k(k))}{\text{max}(x_i^0(k)) - \text{min}(x_i^0(k))}
\]

For the Larger-the-better criterion, the normalize data can be expressed as

\[
x_i^*(k) = \frac{x_i^k(k) - \text{min}(x_i^0(k))}{\text{max}(x_i^0(k)) - \text{min}(x_i^0(k))}
\]

where \( x_i^*(k) \) is the value after grey relational generation (normalized value), and \( \text{max}x_i^0(k) \) and \( \text{min}x_i^0(k) \) are the largest and smallest values of \( x_i^0(k) \) for the kth response, respectively, k being 1 for surface roughness and 2 for roundness and 3 for material removal rate. The processed data after grey relational generation was given in Table 7. The normalized values are ranged between zero and one. Larger normalized results mean to the better performance and the best normalized result should be equal to 1.

3.2 Grey relational coefficient

Grey relational coefficients denote the relationship between the ideal and the actual experimental results. Grey relational coefficient \( \gamma_i(k) \) can be calculated as the following:

\[
\gamma_i(k) = \frac{\Delta_{min} + \psi \Delta_{max}}{\Delta_{oi}(k) + \psi \Delta_{max}}
\]

\( 0 < \gamma_i(k) \leq 1 \)

Here, \( \Delta_{oi}(k) = \|x_0^*(k) - x_i^*(k)\| \), \( x_0^*(k) \) is reference sequence and \( x_i^*(k) \) is comparability sequence; \( \Delta_{min} = \min_{\nu i} \min_{\nu k} \Delta_{oi}(k) \) is the minimum value, \( \Delta_{max} = \max_{\nu i} \max_{\nu k} \Delta_{oi}(k) \)
is the maximum value; $\psi$ is the distinguishing coefficient ($\psi \in [0, 1]$) and is used to adjust the difference of the relational coefficient.

Generally, the distinguishing coefficient is assumed as 0.5 to fit the practical requirements and the grey relational coefficient calculated using Eq. (4) was given in Table 8.

3.3 Calculate Grey Relational Grade (GRG)

The grey relational grade $\alpha_i$ with Eq. (5) can be computed by averaging the grey relational coefficients to evaluate the multiple response as a single index as

$$\alpha_i = \frac{1}{n} \sum_{k=1}^{n} y_i(k)$$

(5)

Here, $n$ is the number of performance characteristics. The highest grey relational grade corresponds to the experimental value closest to the ideal normalized value. Thus, higher grey relational grade shows that the corresponding parameter combination is closer to the optimal. According to Eq. (5), the GRG between the process parameters and the performance characteristics is calculated. Grey relational grade as shown in Table 8.

3.4. Optimal grey relational grade

Since higher GRG was desirable, the larger-the-better S/N quality characteristic was used to obtain the optimal combination for multi-response optimization approach for higher GRG is defined as follows:

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

(6)

In Eq. (6), $y_i$ is the $i$th measured experimental results in a run/row and $n$ explains the number of measurements in each test trial/row. S/N ratios of multiple quality characteristics were calculated by using Eq. (6) and were listed in Table 9. The level of a parameter with the highest S/N ratio gives the optimal level. As showed in Fig. 4. The optimal turn-boring parameter setting for the multiple performance characteristic as A(level 3) -B(level 2) -C(level 2) -D(level 3) -E(level 1). Thus, the best parameters combination were concentration of cutting fluid of 25%, temperature of cutting fluid of 22°C, feed rate of 0.250 mm/rev, radial depth of cut of 0.150 mm and cutting speed of 16 m/min, is the optimal process parameter combination. In addition, the difference between the maximum and minimum values for the GRG in Table 9 is 0.595 for the concentration of cutting fluid, 0.373 for the temperature of cutting fluid, 0.650 for the feed rate, 0.317 for radial depth of cut and 2.236 for the cutting speed, It reflects the impact level of the five process parameters on the performance characteristics. And the cutting speed has the most
remarkable influence on the performance characteristics, while the temperature of cutting fluid exhibits the weakest effect.

3.5. Analysis of variance (ANOVA)

The multi objectives are converted into a single object with the help of grey relational analysis. The significant contribution of each input parameter on the responses in turn-boring parameters is studied by using analysis of variance. The results of the ANOVA are shown in Table 10. As in the ANOVA table of GRG, This indicates that the cutting speed is the most contributing factor.

3.6 Prediction of grey relation grade

After finding the suitable optimal parameters, it is necessary to predict the grey relational grade theoretically. The estimated grey relational grade of the optimal level of the design parameters combination can be calculated as:

$$\gamma_{pre} = \gamma_m + \sum_{i=1}^{k} (\gamma_i - \gamma_m)$$

where \( \gamma_{pre} \) is the GRG to predict the optimal machining parameters, \( \gamma_m \) is the total average GRG, \( \gamma_i \) is the average GRG at the optimal level, and \( k \) is the number of main design parameters that significantly affect the multiple performance characteristics. Table 11 shows the comparison results of the initial turn-boring and optimal turn-boring parameters.

3.7 Experimental validation

In the last step, the obtained results are conducted to verify the optimized solution. Table 11 compares the confirmation test results using the initial and optimal level combination of process parameters. It is obvious that machining with the optimum parametric combination would minimize \( R_a \) from 0.45\( \mu \)m to 0.28\( \mu \)m, \( E_r \) from 3.98\( \mu \)m to 2.56\( \mu \)m and increase MRR from 0.004887(\( mm^3/min \)) to 0.0137550(\( mm^3/min \)). It indicates that the GRA algorithm can be used to improve the performance characteristics.

4. Conclusions

In this study, an innovative precision turn-boring has successfully demonstrated the application of the Taguchi-based grey relational analysis for multi-objective optimization of process parameters in turn-boring 15-5PH stainless steel for achieving for simultaneous
minimum surface roughness, roundness error and maximum MRR. From experimental studies performed in this research the following conclusions can be drawn.

1. The optimum parameters for multiple parameters optimization setting were found to be concentration of cutting fluid of 25%, temperature of cutting fluid of 22°C, feed rate of 0.250mm/rev, radial depth of cut of 0.150mm and cutting speed of 16 m/min.

2. It was observed through ANOVA that the cutting speed is the most influential control factor among the five turn-boring process parameters investigated in this study, when both minimization of surface roughness, roundness error and maximization of material remove rate is considered simultaneously.

3. The percentage improvement in GRG with the multiple responses was 75.72%. It is clearly shown that the performance indicators (surface roughness, roundness error and material remove rate) are significantly improved in the turn-boring 15-5PH stainless steel using the Taguchi-based grey rational analysis.

Table 7 Normalized sequence after grey relational generation.

| Expt. no | Ra (µm) | Er (µm) | MRR (mm³/min) | Normalized values |
|----------|---------|---------|---------------|------------------|
| 1        | 0.28    | 3.41    | 0.0120960     | 0.681818 0.318436 0.632604 |
| 2        | 0.37    | 2.83    | 0.0126307     | 0.477273 0.642458 0.665018 |
| 3        | 0.40    | 2.48    | 0.0032234     | 0.409091 0.837989 0.094744 |
| 4        | 0.16    | 3.73    | 0.0043348     | 0.954545 0.139665 0.162117 |
| 5        | 0.53    | 3.59    | 0.0049885     | 0.113636 0.217877 0.201745 |
| 6        | 0.14    | 2.37    | 0.0031135     | 1 0.899441 0.088081 |
| 7        | 0.45    | 3.98    | 0.0048873     | 0.295455 0 0.195610 |
| 8        | 0.33    | 3.15    | 0.0137550     | 0.568182 0.463687 0.733173 |
| 9        | 0.22    | 2.61    | 0.0031851     | 0.818182 0.765363 0.092422 |
| 10       | 0.47    | 2.36    | 0.0065067     | 0.25 0.905028 0.293779 |
| 11       | 0.42    | 3.68    | 0.0016605     | 0.363636 0.167598 0 |
| 12       | 0.19    | 3.01    | 0.0062313     | 0.886364 0.541899 0.277084 |
| 13       | 0.49    | 3.24    | 0.0073360     | 0.204545 0.413408 0.344051 |
| 14       | 0.20    | 2.27    | 0.0045786     | 0.863636 0.955307 0.176896 |
| 15       | 0.17    | 2.95    | 0.0063747     | 0.931818 0.575419 0.285777 |
| 16       | 0.32    | 2.83    | 0.0181566     | 0.590909 0.642458 1 |
| 17       | 0.38    | 2.84    | 0.0042044     | 0.454545 0.636872 0.154212 |
| 18       | 0.44    | 2.58    | 0.0064512     | 0.318182 0.782123 0.290414 |
| 19       | 0.39    | 2.19    | 0.0024419     | 0.431818 1 0.047369 |
| 20       | 0.15    | 3.26    | 0.0091637     | 0.977273 0.402235 0.454847 |
| 21       | 0.23    | 2.31    | 0.0095687     | 0.795455 0.932961 0.479398 |
| Expt. no | Ra coefficient | Er coefficient | MRR coefficient | Grey relational grades |
|---------|----------------|----------------|----------------|------------------------|
| 1       | 0.6111         | 0.4232         | 0.5764         | 0.5369                 |
| 2       | 0.4889         | 0.5831         | 0.5988         | 0.5569                 |
| 3       | 0.4583         | 0.7553         | 0.3558         | 0.5231                 |
| 4       | 0.9167         | 0.3676         | 0.3737         | 0.5527                 |
| 5       | 0.3607         | 0.3900         | 0.3851         | 0.3786                 |
| 6       | 1.0000         | 0.8326         | 0.3541         | 0.7289                 |
| 7       | 0.4151         | 0.3333         | 0.3833         | 0.3772                 |
| 8       | 0.5366         | 0.4825         | 0.6520         | 0.5570                 |
| 9       | 0.7333         | 0.6806         | 0.3552         | 0.5897                 |
| 10      | 0.4000         | 0.8404         | 0.4145         | 0.5516                 |
| 11      | 0.4400         | 0.3753         | 0.3333         | 0.3829                 |
| 12      | 0.8148         | 0.5219         | 0.4089         | 0.5818                 |
| 13      | 0.3860         | 0.4602         | 0.4325         | 0.4262                 |
| 14      | 0.7857         | 0.9180         | 0.3779         | 0.6939                 |
| 15      | 0.8800         | 0.5408         | 0.4118         | 0.6109                 |
| 16      | 0.5500         | 0.5831         | 1.0000         | 0.7110                 |
| 17      | 0.4783         | 0.5793         | 0.3715         | 0.4764                 |
| 18      | 0.4231         | 0.6965         | 0.4134         | 0.5110                 |
| 19      | 0.4681         | 1.0000         | 0.3442         | 0.6041                 |
| 20      | 0.9565         | 0.4555         | 0.4784         | 0.6301                 |
| 21      | 0.7097         | 0.8818         | 0.4899         | 0.6938                 |
| 22      | 0.5116         | 0.4173         | 0.4051         | 0.4447                 |
| 23      | 0.4583         | 0.6416         | 0.4585         | 0.5195                 |
| 24      | 0.3333         | 0.8483         | 0.4933         | 0.5583                 |
| 25      | 0.7586         | 0.5071         | 0.3403         | 0.5353                 |
| 26      | 0.4783         | 0.6557         | 0.3573         | 0.4971                 |
| 27      | 0.5116         | 0.8174         | 0.4837         | 0.6042                 |

Table 8. Grey relational coefficients and grey relational grades for different performance
Table 9. Response table for S/N ratio of average grey relational grade.

| Level | Concentration | Temperature | Feed rate | Radial depth of cut | Cutting speed |
|-------|---------------|-------------|-----------|---------------------|---------------|
| 1     | -5.621        | -5.472      | -5.602    | -5.307              | -4.389        |
| 2     | -5.367        | -5.099*     | -4.952*   | -5.512              | -5.000        |
| 3     | -5.026*       | -5.443      | -5.460    | -5.195*             | -6.625        |
| Max-Min | 0.595      | 0.373       | 0.650     | 0.317               | 2.236         |
| Ranking | 3            | 5           | 2         | 4                   | 1             |

Fig. 4 Main effects plot of S/N ratios for grey relational grade

Table 10. ANOVA table for grey relational grade

| Factors | DoF | Sum of Squares | Mean of Square | F Value | p Value |
|---------|-----|----------------|----------------|---------|---------|
| A       | 2   | 0.004548       | 0.002274       | 0.27    | 0.770   |
| B       | 2   | 0.002433       | 0.001216       | 0.14    | 0.868   |
| C       | 2   | 0.009498       | 0.004749       | 0.56    | 0.584   |
| D       | 2   | 0.002896       | 0.001448       | 0.17    | 0.846   |
| E       | 2   | 0.087420       | 0.043710       | 5.12    | 0.019   |
| Error   | 16  | 0.136612       | 0.008538       |         |         |
| Total   | 26  | 0.243407       |                |         |         |
Table 11. Comparison of the initial and optimized results.

| Response parameters          | Initial                          | Predicted                        | Experimental | Improvement rate (%) |
|------------------------------|----------------------------------|----------------------------------|--------------|----------------------|
| Level A                      | A₁B₂C₂D₂F₃                      | A₃B₂C₂D₃F₁                      | A₃B₂C₂D₃F₁   | 37.78                |
| Surface roughness            | 0.45                             | 0.28                             |              | 37.78                |
| Roundness error              | 3.98                             | 2.56                             |              | 35.67                |
| Material Removal Rate        | 0.004887                         | 0.0137550                        | 0.0137550    | 181.46               |
| Grey relational grade        | 0.3772                           | 0.6752                           | 0.6628       | 75.72                |

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