Optimization of dressing parameters of grinding wheel for 9CrSi tool steel using the taguchi method with grey relational analysis

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Abstract. This study aims to optimize the dressing parameters of grinding wheel for 9CrSi tool steel to minimize roughness average and flatness tolerance using Taguchi method and Grey Relational Analysis (GRA). These objectives are minimized by optimizing four four-level and two two-level dressing parameters in sixteen experiments based on an orthogonal array L16(4⁴×2²). Taguchi method and GRA are combined to solve the multi-objective optimization problem and determine optimal dressing parameter level combination. Results show that, the optimal dressing parameters to obtain the minimal roughness average and flatness tolerance are coarse dressing depth of 0.025 mm, coarse dressing times of 3 times, fine dressing depth of 0.005 mm, fine dressing times of 2 times, non-feeding dressing of 3 times and dressing feed rate of 1.6 m/min, respectively. Experiments with the optimized dressing parameters have been done to verify the predict model. Results of the roughness average and flatness tolerance from the experiments match with those values of the models and satisfy practical requirements.

1. Introduction

Grinding process plays an important role in the quality of a surface finish [1-3]. This complex process depends on many factors such as grinding wheels, grinding parameters, dressing conditions. During grinding process, the surface of a grinding wheel is continuously worn and that reduces the accuracy of surface finish. To obtain a better grinding performance, the profiles and sharp levels of grinding wheel need to be stably maintained during grinding process. It is necessary to dress the grinding wheel to achieve the original requirements of the workpiece by using dressing tools such as a diamond. In the dressing process, dull grains are removed or severed to re-sharp and renew the cutting face of the grinding wheel.

Many studies have been done to understand the influence of dressing conditions on grind wheels and surface finish [4-16]. Normally, the objective of grinding process is to get a better surface finish (roughness, flatness tolerance, etc.) or high material removal rate of the workpiece. To obtain those objectives, many researchers have tried to optimize dressing parameters [17-25]. For example, the dressing speed ratio, the radial in-feed of the diamond roller dresser and the dress-out time are optimized to determine the grinding wheel lifetime, the cutting ability of the abrasive wheels, the cutting forces, and the roughness of the machined surfaces [23]. In the same study [25], the dressing depth of cut, the dressing cross feed rate, the drag angle of dresser, and the number of passes are...
investigated to minimize surface roughness. To optimize dressing parameters, many optimization methods are used such as simulated annealing method, neutral network method, Taguchi method and Grey Relational Analysis (GRA) method [17-27].

Although many published researches are available to optimize dressing parameters, there are still many parameters that have not been studied yet such as the effect of three dressing states i.e. the coarse dressing, the fine dressing and non-feeding dressing on the surface finish. In this study, six dressing parameters, including dressing feed rate, coarse dressing depth, coarse dressing times, fine dressing depth, fine dressing times, and non-feeding dressing are optimized to grind 9CrSi alloy steel workpiece on a surface grinding machine to minimize surface roughness and flatness tolerance. The coarse dressing depth, the fine dressing depth, the fine dressing times, and non-feeding dressing are set up in four four-level while the others two-level dressing parameters. Sixteen experiments are arranged based on an orthogonal array L_{16}(4^4×2^2). Two objectives i.e. the roughness average and the flatness tolerance are minimized by combination of Taguchi and GRA methods [28-32].

2. Methodology

2.1 Experimental machine and equipment
In this study, the grinding and dressing processes are implemented in a surface grinding machine as shown in Figure 1. The workpieces are made by 9CrSi tool steel (C: 0.85-0.95%, Si: 1.2-1.6%, Mn: 0.3-0.6%, Cr: ≤ 0.95-1.25%, P, S: ≤ 0.03%, Mo, W: ≤ 0.2%, Ni: ≤ 0.35%, V: ≤ 0.15%) with dimensions of 100×60×20 mm and hardness of 58-62 HRC. Lubricant is used in grinding process is Cantex Aquatex 3810 with flow of 10 l/min. All experiments are done on the devices that are listed in Table 1.

![Figure 1. Surface grinding process.](image)

### Table 1. Experimental equipment.

| Machine and Equipment                      | Specification                      |
|-------------------------------------------|------------------------------------|
| Surface grinding machine                  | MOTO – YOKOHAMA                    |
| Grinding wheel                            | Cn46TB2GV1.300.32.127.30 m/s       |
| Dressing tool                             | 3908-0088C type 2                  |
| Roughness measurement device              | Mitutoyo 178-923-2A, SJ-201        |
| Flatness tolerance measurement device     | Mitutoyo CMM544                    |

2.2 Design experiment
Grinding process parameters at each experiment are a cutting velocity of 26.7 m/sec, a depth of cut of 0.01 mm, a workpiece velocity of 10 m/min and an axial feed velocity of 8 mm/pass. Based on previous studies [17-27], six dressing parameters, including the dressing feed rate, the coarse dressing depth, the coarse dressing times, the fine dressing depth, the fine dressing times, and the non-feeding
dressing are selected to investigate the roughness and flatness tolerance of the machined surfaces in this research. Each of these parameters is set up as shown in Table 2 in which there are four four-level factors and two two-level factors. The design of experiment (DOE) method has been used for the experiments consist of identical L16 orthogonal array fractional parametrical designs in seven first columns in Table 3.

### Table 2. Dressing parameters and levels

| Parameters                  | Unit   | Levels          |
|-----------------------------|--------|-----------------|
| Dressing feed rate $S$      | m/min  | 1.6 1.8 - -     |
| Coarse dressing depth $t_{coarse}$ | mm     | 0.015 0.02 0.025 0.03 |
| Coarse dressing times $n_{coarse}$ | Times | 0 1 2 3 |
| Fine dressing depth $t_{fine}$ | mm     | 0.005 0.01 - - |
| Fine dressing times $n_{fine}$ | Times | 0 1 2 3 |
| Non-feeding dressing $n_{non-feed}$ | Times | 0 1 2 3 |

### Table 3. L₁₆ Orthogonal array with factors and responses

| No. | $t_{coarse}$ | $n_{coarse}$ | $n_{non-feed}$ | $n_{fine}$ | $S$ | Surface roughness | Flatness tolerance |
|-----|--------------|--------------|----------------|------------|----|-----------------|-------------------|
|     |              |              |                |            |    | average Ra (µm) | FT (µm)           |
|     |              |              |                |            |    | Trial 1 | Trial 2 | Trial 3 | Trial 1 | Trial 2 | Trial 3 |
| 1   | 0.015        | 1            | 0              | 0          | 0.005 | 1.6     | -       | -         | -       | -       | -       |
| 2   | 0.15         | 1            | 1              | 1          | 0.005 | 1.8     | 1.514   | 1.117     | 1.229   | 27.4    | 27.6    | 26.35   |
| 3   | 0.15         | 2            | 2              | 2          | 0.01  | 1.6     | 0.745   | 0.825     | 0.842   | 24.65   | 24.4    | 25.4    |
| 4   | 0.15         | 3            | 3              | 3          | 0.01  | 1.8     | 0.652   | 0.517     | 0.596   | 17.15   | 19.4    | 19.6    |
| 5   | 0.02         | 2            | 1              | 2          | 0.01  | 1.8     | 1.225   | 1.042     | 1.252   | 16.15   | 16.7    | 17.4    |
| 6   | 0.02         | 1            | 0              | 3          | 0.01  | 1.6     | 1.267   | 1.322     | 1.35    | 16.35   | 16.6    | 17.55   |
| ... |              |              |                |            |       |         |         |           |         |         |         |
| 15  | 0.03         | 2            | 1              | 3          | 0.005 | 1.6     | 0.635   | 0.769     | 0.677   | 18.3    | 20.35   | 19.65   |
| 16  | 0.03         | 3            | 0              | 2          | 0.005 | 1.8     | 0.771   | 0.874     | 0.892   | 16.3    | 18.65   | 17.1    |

2.3 Measurement
After each experiment, roughness is measured at three locations and these three roughness values are averaged. Flatness tolerance is determined by the difference of the maximum height and minimum height in 27 measured points on the workpiece. The roughness and flatness are measured three times at each experiment and their values are recorded in six last columns in Table 3.

3. Results and discussion
After all experiments are done as in Table 3, GRA [28-32] is used to solve multi-objective optimization problem in which the roughness average and flatness tolerance of the workpiece are minimized simultaneously. Then, Taguchi method is used to analysis and determine the optimal dressing parameters.

In the first step to optimize dressing parameters, based on the measured results, the grey relational grades ($\gamma$) are generated as shown in Table 4.
Table 4. Grey relational co-efficient and grey grade values

| No. | Grey relational co-efficient \( \gamma_i \) | \( \gamma \) |
|-----|---------------------------------|------|
|     | Ra | FT |                      |
| 1   | 0.361 | 0.333 | 0.347 |
| 2   | 0.488 | 0.351 | 0.419 |
| 3   | 0.690 | 0.420 | 0.555 |
| 4   | 0.359 | 0.457 | 0.408 |
| 5   | 0.333 | 0.455 | 0.394 |
| ... |     |     |                  |
| 15  | 0.566 | 0.410 | 0.488 |
| 16  | 0.465 | 0.444 | 0.455 |

From Table 4, the higher grey relation grade implies the better product quality. Therefore, the factor effects can be estimated and the optimal level for each controllable factor determined. By observation of the grey relational grade corresponding to each experiment, the 10th experiment \( (t_{\text{coarse}3}, n_{\text{coarse}2}, n_{\text{non-feed}4}, n_{\text{fine}3}, t_{\text{fine}1}, S_1) \) has the maximum grey relational grade. That means that in this experiment, the S/N ratio is close to the normalized S/N ratio and it have better properties than other experiments. However, this result does not show optimal dressing parameters.

After that, in order to find these optimal factors, Taguchi method is used to determine the relation between the dressing parameters in different levels and grey relation grades as shown in Table 5. In addition, the effects of dressing parameters on the grey relation grades are plotted in Figure 2.

Table 5. Main effects on grey relation grades

| Level | \( t_{\text{coarse}} \) | \( n_{\text{coarse}} \) | \( n_{\text{non-feed}} \) | \( n_{\text{fine}} \) | \( t_{\text{fine}} \) | \( S \) |
|-------|----------------|----------------|----------------|----------------|----------------|-----|
| 1     | 0.4405 | 0.4645 | 0.4657 | 0.4694 | **0.5216** | **0.6009** |
| 2     | 0.4532 | 0.5317 | 0.4706 | 0.5401 | 0.4984 | 0.429 |
| 3     | **0.6345** | 0.4596 | 0.4457 | **0.5705** |       |     |
| 4     | 0.4914 | **0.5694** | **0.644** | 0.4469 |       |     |
| Delta | 0.194 | 0.1098 | 0.1982 | 0.1236 | 0.0231 | 0.172 |
| Order of effect | 2 | 5 | 1 | 4 | 6 | 3 |

Average of grey relation grades (T) is **0.509217**

As observing in Table 5 and Figure 2, the optimal dressing parameters for surface grinding process to maximize the grey relation grade are \( t_{\text{coarse}3}/n_{\text{coarse}2}/n_{\text{non-feed}4}/n_{\text{fine}3}/t_{\text{fine}1}/S_1 \) or \( t_{\text{coarse}}=0.025 \text{mm}, n_{\text{coarse}} = 3 \text{ times}, n_{\text{non-feed}} = 3 \text{ times}, n_{\text{fine}} = 2 \text{ times}, t_{\text{fine}} = 0.005 \text{ mm}, S = 1.6 \text{ m/min} \).

Then, ANOVA table is established as presented in Table 6 to determine how much contribution of each dressing parameter on the grey relation grade. Based on the value of contribution in the last column in Table 6, the non-feeding dressing is the most significant parameter with a contribution of 26.5%, followed by the fine dressing times of 25%, and the coarse dressing depth of 18.7%. The fine dressing depth and coarse dressing times with contribution of 7.4% and 6.3% are the less significant. Since the contribution of the feed rate is very small, the influence on the surface finish of this parameter can be negligible.
From above results, the predict modal of the optimal grey relation analysis are determined by the following equation:

\[ \gamma_{op} = t_{\text{coarse}} + n_{\text{coarse}} + n_{\text{non-feed}} + n_{\text{fine}} + t_{\text{fine}} - 4T \]  

(1)

where \(T\) is the average of grey relation grades (\(T = 0.509217\) as in Table 5), with the values of \(t_{\text{coarse}}, n_{\text{coarse}}, n_{\text{non-feed}}, n_{\text{fine}}, t_{\text{fine}}, S_1\) taken from Table 5. Using these optimal dressing parameters, the minimal values of roughness average and flatness tolerance are computed as:

\[ (Ra, FT)_{\text{min}} = t_{\text{coarse}} + n_{\text{coarse}} + n_{\text{non-feed}} + n_{\text{fine}} + t_{\text{fine}} - 4T \]  

(2)

where \(t_{\text{coarse}}, n_{\text{coarse}}, n_{\text{non-feed}}, n_{\text{fine}}, t_{\text{fine}}\) are mean values of the roughness average or the flatness tolerance corresponding with the coarse dressing depth at the level 3, the coarse dressing times at the level 4, the non-feed dressing at the level 4, the fine dressing depth at the level 3, and the fine dressing times at the level 1, respectively. Therefore, the predict values of the roughness average and the flatness tolerance are calculated as \((Ra)_{\text{min}} = 0.3399\mu m\) and \((FT)_{\text{min}} = 10.3\mu m\).

Finally, to evaluate the predict model, experiments have been done with the optimal dressing parameters in two times and their results are shown in Table 7. In this table, the differences of the surface finish properties between the predict model and experiment are small. Thus, the proposed
method has been proven and it can be used to accurately predict both the roughness average and flatness tolerance simultaneously.

| Properties of surface finish | Optimal parameters | Error (%) |
|------------------------------|--------------------|----------|
| Roughness average: Ra (µm)   | t_{coarse}, n_{coarse}, n_{non-feed}, n_{fine}, t_{fine}, S | 0.3399   | 0.358 | 5.3 |
| Flatness tolerance: FT(µm)   |                    | 10.3     | 10.98| 6.6 |
| GRA value                    |                    | 0.9031   | 0.836|     |

**Table 7. The results from model and experiment**

4. Conclusion
This study has been done to optimize the dressing parameters of grinding wheel for 90CrSi tool steel to minimize the roughness average and the flatness tolerance using Taguchi method and Grey Relational Analysis. Sixteen surface grinding experiments are set up based on an orthogonal array L_{16}(4^4 x 2^2) for four four-level and two two-level parameters, including the dressing coarse dressing depth, the fine dressing depth, the fine dressing times, the non-feeding dressing, the dressing feed rate and, the coarse dressing times, respectively. Based on the results of GRA and Taguchi method, the optimal dressing parameters are determined to minimize the roughness average and flatness tolerance. Results show that the coarse dressing depth, the coarse dressing times, the fine dressing depth, the fine dressing times and the non-feed dressing are significant factors while the feed rate $S$ is not important factor. The optimal dressing parameters that should be used for surface grinding process of 90CrSi alloy steel to obtain the minimal the roughness average and the flatness tolerance are $t_{coarse}=0.025$ mm, $n_{coarse}= 3$ times, $n_{non-feed}= 3$ times, $n_{fine}= 2$ times, $t_{fine}= 0.005$ mm, $S= 1.6$ m/min. In addition, the predict results agree with the experiment results, thus the proposed method in this study has been verified. This method can be further applied to optimize other mechanical manufacturing processes.

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