Analysis of surface hardness and surface roughness in diamond burnishing of 17-4 PH stainless steel

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Abstract. Burnishing is a chipless secondary finishing operation which yields excellent surface finish. The present work focuses on multi-response optimization of diamond burnishing on 17-4 precipitation hardenable stainless steel under dry environment by using Taguchi based grey relation analysis (TGRA) to simultaneously minimize surface roughness and maximize surface hardness. The effect of the process parameters such as burnishing speed, burnishing feed and burnishing force on performance characteristics like surface roughness and surface hardness were studied. Taguchi's L₉ orthogonal array has been adopted for the experimental design. The optimal burnishing process parameters were found to be burnishing speed of 73 m/min, burnishing feed of 0.048 mm/rev and burnishing force of 150 N. Burnishing feed is the most significant parameter on burnishing performance characteristics. It has been proved that the performance characteristics of a diamond burnishing process have been improved by effective use of this technique.

Keywords: Optimization, GRA, surface roughness, surface hardness, ANOVA.

1. Introduction
Quality of the surface is one of the important factor based on which the performance of the product will be decided. In order to obtain a high-quality surface, finishing operation has to be performed on a machined surface. Burnishing is one such technique where the high-quality surface can be achieved with the help of a specific tool. It is a type of surface modification process and doesn't involve the material removal from the workpiece. Instead of that, the tool pushes the material to flow into the valleys from the peaks which result in reduced surface roughness and improved surface hardness. In the present work diamond burnishing tool has been used to finish the workpiece to obtain high-quality surface. The tip of the tool is made up of pure diamond and hence it is possible to burnish hard materials. The adaptability of this process has drawn a lot of interests among researchers across the world. The work material used for the present investigation is 17-4 PH stainless steel. It is one of the hard materials and its wide range of applications in a variety of fields has attracted researchers to concentrate more on it.

Extensive research work has been carried out on burnishing as well as Taguchi based grey relation analysis. Korhonen et al. [1] has compared the performance of PCD and amorphous coated diamond tip on Nitronic 50 HS specimens. It was found that working with amorphous coated diamond tip will be very difficult compared to PCD insert. Drastic improvement has been observed in the surface topography of the specimen after working with amorphous coated diamond tip. Chomienne et al. [2] compared turning and burnishing process by using 15-5 PH stainless steel specimen. It was proved that burnishing force is the parameter which will have more impact on the residual stress of the specimen and burnishing was proved to be the best method when compared to turning. Low and Wong [3] proved that surface finish of some special polymers like POM and PUR can be enhanced with the help of ball burnishing tool. Hassan and Al-Bsharat [4] explained about the application of different diameter balls on nonferrous metals and proved that with smaller diameter ball, the hardness and with
larger diameter ball, the surface finish can be enhanced respectively. El-Tayeb et al. [5] developed a new tool with an interchangeable adapter to burnish aluminium 6061 disc. Tribotest machine was used to burnish the disc. It was found that, surface roughness can be reduced with smaller diameter roller when compared to higher diameter roller. The higher speed will affect the improvement in hardness of the specimen. Okada et al. [6] proposed a new method to improve the surface finish of the workpiece by roller burnishing. It was found that surface finish was enhanced by increasing the thrust force and minimizing the feed rate. Revankar et al. [7] has carried out an analysis on the surface roughness and hardness of titanium alloy. Optimization has been carried out by using Taguchi technique. It has been proved that the parameters responsible for the improvement of surface finish were feed and speed. Surface hardness was increased by increasing the force and number of tool pass. Hassan et al. [8] utilized Response surface methodology optimization technique to optimize the process factors of ball burnishing process on a brass specimen. A surface roughness of 0.172µm was obtained for the optimal values. Basak and Goktas [9] studied the effect of process parameters on burnishing of Al7075 T6. The fuzzy logic model has been established to compare the experimental values with the theoretical model to get the optimum parameter to carry out the burnishing process. A very small deviation between the experimental values and fuzzy logic results has been observed. Hassan [10] developed a new tool to burnish Al-Cu cast components. It has been proved that burnishing process has improved the surface characteristics. Increase in speed, feed and force causes the surface roughness to decrease up to a certain limit, then it increases and also when the force is more the hardness increases. If the speed and feed were increased, hardness decreases. Zhang et al. [11] showed that 17-4 PH stainless steel yields the best result after burnishing operation and it has been suggested to be the better material for the aerospace application. Hamadache et al. [12] used roller and ball burnishing process to analyze the performance characteristics of Rb40 steel. Performance characteristics like surface roughness and hardness have been analyzed. Number of tool pass and force were proved to be the important parameter which affects the surface integrity of Rb40 steel.

Most of the researchers have successfully implemented the Taguchi coupled grey relational analysis to various machining processes. Chakradhar and Venu [13] optimized the process parameters of electrochemical machining (ECM) of EN 31 steel by using TGRA. It was noticed that feed rate is the most significant parameter which affects the ECM robustness. Sivaiah and Chakradhar [14] carried out multi-objective optimization of cryogenic turning process on 17-4 PH stainless steel by using GRA. It was concluded that feed rate is the most significant parameter on turning performance characteristics. Wan et al. [15] investigated the weld quality characteristics in spot welding of titanium alloy. Optimum welding parameters have been obtained by using GRA. It was concluded that welding current is one of the parameters which plays a key role in improving the quality of welding. Eshtayeh and Hrairi [16] obtained the optimal process parameters of mechanical clinching of dissimilar materials to achieve the high strength of the joint by using GRA. Ghetiya et al. [17] used Taguchi based GRA to obtain the GRG for friction stir welding of aluminium alloy with multiple characteristics. It was shown that rotational speed and welding speed are the two most significant parameters which have an impact on the process. Vishwas et al. [18] studied the surface integrity properties of AISI 410 martensitic stainless steel by turning operation under dry condition.

Few efforts have been made by previous researchers to understand the effects of diamond burnishing parameters on different work materials. In this work, diamond burnishing tool was used to carry out the burnishing process on 17-4 PH stainless steel under dry environment. However this material is having a wide range of applications in industrial sectors, it is necessary to carry out multi-performance optimization of diamond burnishing process parameters. The burnishing process parameters used were burnishing force, burnishing speed and burnishing feed. The L9 orthogonal array has been applied based on Taguchi technique.

2. Materials and method
The experimental set up used for dry diamond burnishing is as shown in Fig. 1. The experiments have been performed by using a conventional ‘Kirloskar’ lathe. The work material used for the research
work has a dimension of 30 mm diameter and 150 mm length. The diamond burnishing tool is used to carry out the experiments. The process parameters considered were burnishing speed, burnishing feed and burnishing force. Surface roughness was measured by using ‘Mitutoyo’ surface roughness tester of type SJ301. Surface hardness was measured by using Vickers hardness tester. Three sampling readings were taken on each burnished workpiece and the average of three sampling readings was taken as the final surface roughness and surface hardness measurement. The optimal burnishing process parameters were obtained by using Taguchi’s L₉ orthogonal array. The number of process parameters and their levels is as shown in Table 1. Experimental results obtained for Taguchi’s L₉ orthogonal array is as depicted in Table 2.

Table 1. Experimental information

| Burnishing process parameters | Levels                  |
|------------------------------|-------------------------|
| Burnishing speed (A):        | 21, 73, 113 m/min       |
| Burnishing feed (B):         | 0.048, 0.065, 0.096 mm/rev |
| Burnishing force (C):        | 20, 90, 150 N           |

Table 2. Results for surface roughness Ra (µm) and surface hardness H (HV)

| Sl. No. | A    | B   | C   | Ra (µm) | S/N ratio for Ra | H (HV) | S/N ratio for H |
|---------|------|-----|-----|---------|-----------------|--------|-----------------|
| 1       | 21   | 0.048 | 20   | 0.24    | 12.3958         | 369    | 51.3405         |
| 2       | 21   | 0.065 | 90   | 0.16    | 15.9176         | 366    | 51.2696         |
| 3       | 21   | 0.096 | 150  | 0.29    | 10.7520         | 392    | 51.8657         |
| 4       | 73   | 0.048 | 90   | 0.12    | 18.4164         | 374    | 51.4574         |
| 5       | 73   | 0.065 | 150  | 0.13    | 17.7211         | 392    | 51.8657         |
| 6       | 73   | 0.096 | 20   | 0.25    | 12.0412         | 356    | 51.0290         |
| 7       | 113  | 0.048 | 150  | 0.19    | 14.4249         | 402    | 52.0845         |
| 8       | 113  | 0.065 | 20   | 0.20    | 13.9794         | 350    | 50.8814         |
| 9       | 113  | 0.096 | 90   | 0.29    | 10.7520         | 352    | 50.9309         |

Figure 1. Diamond burnishing process
3. Optimization steps using the TGRA

Taguchi method is one of the best methods to simplify the optimization of process parameters. Grey relation analysis is one of the simplest methods to convert multi-performance characteristics into a single objective optimization problem. The following steps have been used in TGRA.

3.1 Step 1: Calculation of grey relational generation

In this step, the responses obtained are normalized to reduce the variability. Raw data is difficult to compare, hence the data sequence has to be normalized between the values 0 to 1. In this step based on the output responses, two methods have been followed. ‘Larger the better’ and ‘smaller the better’ approaches. For surface roughness smaller the better (Equation (1)) and for surface hardness larger the better (Equation 2) approach has been followed because after diamond burnishing process, the surface roughness has to be minimized and surface hardness has to be maximized. The following Equations (1) and (2) have been used for normalization sequence [13]. The normalized experiment results computed with Equations (1) and (2) are as tabulated in Table 3.

\[ D_i(r) = \frac{\max E_i(r) - E_i(r)}{\max E_i(r) - \min E_i(r)} \] (1)

\[ D_i(r) = \frac{E_i(r) - \min E_i(r)}{\max E_i(r) - \min E_i(r)} \] (2)

3.2 Step 2: Grey relational coefficient

To know the relationship between the desirable and real experimental data, grey relational coefficient has been calculated. The grey relation coefficient can be obtained by using equation 3 [14]. Table 4 tabulates grey relation coefficient and grey relation grade.

\[ \epsilon_i = \frac{\Delta_{\text{min}} + \zeta \Delta_{\text{max}}}{\Delta_{oi}(r) + \zeta \Delta_{\text{max}}} \] (3)

Where \( \Delta_{oi}(r) \) indicates absolute sequence deviation of sequence reference \( D_o(r) \) and comparability sequence \( D_i(r) \), i is the number of characteristics (1, 2, 3, 4) and r is the number of experimental runs (1, 2, ………., 9). Hence \( \Delta_{oi}(r) \) can be written as:

\[ \Delta_{oi}(r) = |D_o(r) - D_i(r)| \] (4)

\[ \Delta_{\text{min}} = \min_r \Delta_{oi}(r) \] (5)

\[ \Delta_{\text{max}} = \max_r \Delta_{oi}(r) \] (6)

3.3 Step 3: Grey relational grade

It has been calculated by using a weighing method which integrates the obtained grey relation coefficient. It can be determined by using Equation (7) [15].

\[ \gamma_i(r) = \frac{1}{N} \sum_{i=0}^{\omega_i \ast \epsilon_i(r)} = \frac{1}{N} \sum_{i=0}^{\omega_i \ast \epsilon_i(r)} \] (7)

Where

\( N = \) is the number of performance characteristics

\( \omega_i = \) weights. In this research, it is assumed that all control factors have equal importance.

4. Results and discussion

Considering the surface roughness and surface hardness as the most important output responses, equal weighting has been allotted to both the responses. From Table 4, it has been observed that experiment number 5 has highest weighted grey relational grade out of 9 experiments and also the two objective complicated multi-performance optimization problem is converted to the single objective optimization problem using weighted grey relational grade. The means of a grey relational grade for each level of
process parameters namely burnishing speed, burnishing feed and burnishing force were calculated using Minitab 17.0 software and tabulated in Table 5. Fig. 2. depicts the grey relational grade obtained for each process parameter and at each level. The combination of A₂B₂C₃ yields the highest value of grey relational grade for the factors A, B and C. The larger the grey relational grade the closer is the response to ideal value and optimum performance will be delivered. The optimized process parameters are found to be the burnishing speed of 73 m/min, the burnishing feed of 0.048 mm/rev and burnishing force of 150 N.

![Figure 2. Effect process parameters on grey relation grade](image)

| Trial No. | Ra   | H    |
|-----------|------|------|
| 1         | 0.294| 0.365|
| 2         | 0.765| 0.308|
| 3         | 0.000| 0.808|
| 4         | 1.000| 0.462|
| 5         | 0.941| 0.808|
| 6         | 0.235| 0.115|
| 7         | 0.588| 1.000|
| 8         | 0.529| 0.000|
| 9         | 0.000| 0.038|

Table 3. Normalized response values
Table 4. Grey relation coefficient and grades of grey relation

| Trial No. | Grey relational co-efficient | Grey relational grade |
|-----------|-----------------------------|-----------------------|
|           | Ra  | H   | Magnitude | S/N ratio | Order |
| 1         | 0.415 | 0.441 | 0.428 | -7.37112 | 6     |
| 2         | 0.680 | 0.419 | 0.550 | -5.19275 | 4     |
| 3         | 0.333 | 0.722 | 0.528 | -5.54732 | 5     |
| 4         | 1.000 | 0.481 | 0.741 | -2.60364 | 3     |
| 5         | 0.895 | 0.722 | 0.808 | -1.85177 | 1     |
| 6         | 0.395 | 0.361 | 0.378 | -8.45016 | 8     |
| 7         | 0.548 | 1.000 | 0.774 | -2.22518 | 2     |
| 8         | 0.515 | 0.333 | 0.424 | -7.45268 | 7     |
| 9         | 0.333 | 0.342 | 0.338 | -9.42167 | 9     |

Table 5. Response table for average grey relation grade

| Control factors | Level 1 | Level 2 | Level 3 | Delta | Rank |
|-----------------|---------|---------|---------|-------|------|
| A               | 0.5020  | 0.6423  | 0.5120  | 0.1403 | 3    |
| B               | 0.6477  | 0.5940  | 0.4147  | 0.2330 | 2    |
| C               | 0.4010  | 0.5430  | 0.6345  | 0.2335 | 1    |

5. Analysis of variance (ANOVA)
The contribution of each parameter on grey relation grade has been obtained by ANOVA. It has been carried out for the obtained grey relation grade by using Minitab 17.0 software. From Table 6 it has been concluded that burnishing feed is the most significant parameter with a percentage of contribution of 34.49 followed by the burnishing force with a contribution of 30.86%. A burnishing speed has the least significance with a contribution of 14.17%.

Table 6. ANOVA of grey relation grade

| Factors | Degrees of freedom | Sum of square | Mean square | Factors Contribution (%) |
|---------|--------------------|---------------|-------------|--------------------------|
| A       | 2                  | 0.0367        | 0.0372      | 14.17                    |
| B       | 2                  | 0.0893        | 0.0256      | 34.49                    |
| C       | 2                  | 0.0799        | 0.0399      | 30.86                    |
| Residual error | 2                  | 0.0529        | 0.0264      | 20.43                    |
| Total values | 8                  | 0.2589        |             | 100                      |

6. Confirmation test
The improvement in the performance characteristics can be obtained by performing confirmation test. The estimated grey relational grade can be calculated using Equation (8) [19].

\[
y_{predicted} = y_m + \sum_{i=1}^{k} (y_0 - y_m)
\]

Where ‘\(y_m\)’ is the average of total grey relation grade

‘\(y_0\)’ is the means of GRG at their optimal levels

‘\(k\)’ is the number of machining factors that considerably affects the multiple performance characteristics.
The confirmation test was performed with the predicted optimum settings and obtained experimental results for the parameter setting $A_2B_1C_3$ were tabulated in Table 7. From Table 7 it is seen that the surface roughness decreases from 0.13 $\mu$m to 0.12 $\mu$m and surface hardness increases from 392 HV to 396 HV. The improvement in the GRG has been observed to be 10.81%. Overall an improvement was observed by the effective use of TGRA and hence the predicted optimum burnishing conditions were taken as optimum burnishing conditions while diamond burnishing of 17-4 precipitation hardenable stainless steel under the working range of process parameters respectively.

|       | Initial conditions | Optimal conditions | Prediction | Experimental |
|-------|--------------------|--------------------|------------|--------------|
| Level | $A_2B_2C_3$        | $A_2B_1C_3$        | $A_2B_1C_3$| $A_2B_1C_3$  |
| Ra ($\mu$m) | 0.13             | 0.12               | 0.12       |              |
| H (HV)         | 392              | 396                | 396        |              |
| Grey relation grade | 0.8080        | 0.8844             | 0.9060     |              |

The improvement in grades of grey relation is 0.09
The percentage improvement in GRG is 10.81

7. Conclusions
In this study Taguchi-based, GRA is used for optimizing the diamond burnishing process parameters of 17-4 PH stainless steel under dry environment. The following conclusions were drawn:

- The optimum process parameters were determined as the burnishing speed of 73 m/min, the burnishing feed of 0.048 mm/rev and burnishing force of 150 N.
- At the optimum combination level, the surface roughness decreases from 0.13 $\mu$m to 0.12 $\mu$m and surface hardness increases from 392 HV to 396 HV.
- The improvement in the GRG has been observed to be 10.81%.
- It was observed that burnishing feed (34.49%) is the most significant parameter that affects the diamond burnishing process.
- Taguchi’s grey relation analysis technique has been applied to multi-response optimization problems effectively.

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