Process Parameters Optimization Using Taguchi’s Orthogonal Array and Grey Relational Analysis during Hard Turning of AISI D2 Steel in Forced Air-Cooled Condition

S K Rajbongshi1 and D K Sarma1*
1National Institute of Technology Meghalaya, Shillong, 793003, India
1Email: dksarma@nitm.ac.in, Phone: +919864430524, Fax: +91 364 2501113

Abstract. Optimization of process parameters play an important role in machining operations. The present work deals with a multi-objective optimization method (Grey relational analysis) and Taguchi’s orthogonal array (OA) technique in machining of AISI D2 steel using coated carbide tool in forced air-cooled condition considering it to be environment friendly. The process parameters considered are cutting speed, feed and depth of cut having three levels each. The performance parameters are surface roughness, flank wear and cutting force. Taguchi’s orthogonal array L9 is considered for the experimental design. Grey relational analysis technique is used for finding the optimal settings of the process parameters to obtain the value of surface roughness, flank wear and cutting force. The optimum grey relational grade has been found out to get the optimal setting of the experimental run. Then level wise grey relational grade has been found out from the experimental run for each parameter. The optimal settings based on the rank of the grey relational grade in the experimental run and level wise optimal settings of the parameters from the grey relational grade have been compared. The improvement of performance parameters is confirmed from the grey relational prediction analysis in comparison to optimal values in the experimental run.

1. Introduction
The machining is one of the most important operations in manufacturing sector. Among the different machining operations, turning is mostly used for making different products in manufacturing areas. The turning operation using hard materials is a challenging task for the operator due to the risk of tool failure. To perform the machining operation of the hard materials, researchers are using high grade tool which is highly wear resistant and chemically inert. Researchers are mainly using ceramic and CBN tool for hard turning operations, although some of them used coated carbide tool also. The use and applications of coated carbide tools like TiAlN, TiN, TiCN, TiCON, Al2O3 and ceramic and CBN and PCBN tools in hard machining were stated by Bartarya and Choudhury [1]. The machinability of Stellite 12 alloys using coated and uncoated carbide tools were studied by Shao et al. [2]. Their study revealed that the flank wear of uncoated carbide tool was more than coated carbide tool. Strenkowski et al. used cubic boron nitride (CBN) and improved ceramic cutting tool in machining hardened steel materials to avoid the usage of coolants [3].

Due to the non-linear behaviour of machining operations, it is very difficult to obtain proper machinability by simply choosing the ranges recommended by the manufacturers. Proper setting of the machining operations is a must to obtain the optimal values of the responses. That is why, optimization technique is necessary for every types of machining operations. Taguchi’s optimization
technique is an important optimization tool in machining. Taguchi’s orthogonal array (OA) technique helps to reduce the number of experiments, thereby saving time and cost of machining. These minimum number of experiments can give the optimal values of the responses. Taguchi’s optimization technique is useful for optimizing single response at a time. But when multi-objective optimization criteria come, Taguchi’s optimization technique cannot optimize the all responses at a time. To fulfill this discrepancy in machining, grey relational analysis is found to be an important multi-objective optimization tool which can optimize the several responses at a time. It helps to obtain optimum values of many responses at one particular setting. Gopalsamy used grey relational analysis with Taguchi’s OA and ANOVA to determine the effect of process parameters viz. cutting speed, feed and depth of cut on material removal rate, surface roughness, tool wear and tool life [4]. The authors were able to optimize the machining parameters for optimal response values. Kacal and Yildrim used Taguchi’s OA and grey relational analysis in turning of AISI D6 (60 HRC) steel using ceramic and cubic boron nitride cutting tool [5]. The responses studied were tool wear, surface roughness, machining force and specific cutting force. Using grey relational prediction analysis, they were able to get the optimum values of the responses as compared to the values obtained in the experimental run. Huang and Liao used a combined technique of Taguchi’s OA concept and grey relational analysis to obtain optimum machining parameters in wire-EDM process [6]. Using this method, it was found that material removal rate was mainly influenced by feed rate and pulse on time had significant effect on gap width and surface roughness. Lin used Taguchi’s method and grey relational analysis in multiple performance optimization of tool life, cutting force and surface roughness in machining of S45C steel bars using P20 tungsten carbide tool [7]. The authors found the improvement of response values. Grey relational technique was used by Nayak et al. in optimization of machining parameters to obtain the optimum values of material removal rate, cutting force and surface roughness in dry turning of AISI 304 austenitic stainless steel [8]. Confirmatory test using grey relational analysis gave 88.78% improvement in grey relational grade. Mishra et al. used Taguchi’s L16 orthogonal array along with the grey relational analysis in optimizing process parameters in turning of AA 7075/SiC composite in an environment of dry and spray cooling [9]. The authors reported that the performance of spray cooling was better as compared to dry turning by using grey relational analysis. Sohrabpoor et al. used dry, wet and MQL as the medium of environment in turning of AISI 4340 steel using coated carbide tool [10]. Using grey relational analysis, the authors found that MQL environment method gave lowest surface roughness and tool wear. Patole et al. used grey relational analysis in optimizing machining parameters in turning AISI 4340 steel using tungsten coated carbide inserts in MQL environment [11]. Using grey relational analysis, the authors found the improvement of machinability of AISI 4340 steel using MQL.

From the above literature reviews, it has been observed that the researchers have used Taguchi’s OA array along with the grey relational analysis to perform the multi-objective optimization characteristics and most of them used dry as the working environment. Also, it is observed that very few researchers have used forced air-cooling environment as the medium of operation in optimizing the machining parameters using grey relational analysis. So, in this present work, Taguchi’s OA along with grey relational analysis have been used in optimizing machining parameters in turning of AISI D2 steel using coated carbide tool and forced air-cooled environment as the medium of operation.

2. Experimental set up

2.1. Cutting tool & work piece material
i. Cutting Tool Material: Coated Carbide Tool (Make: Sandvik; Model: SNMG 12 04 08 KM3215).
ii. Work Piece Material (commercially available AISI D2 Steel (hardened to 48 HRC)).

3. Results and discussion
Cutting speed, feed and depth of cut are selected as process parameters and surface roughness (SR), flank wear (FW) and cutting force (CF) as performance parameters. The ranges of the cutting
parameters are selected according to the recommendation of the tool manufacturers and literature. Table 1 shows the cutting parameters with their level.

**Table 1. Cutting parameters with their levels.**

| SI No. | Level (Low) | Level (Medium) | Level (High) |
|--------|-------------|----------------|--------------|
| 1      | v (m/min)   | 100            | 125          | 150          |
| 2      | f (mm/rev)  | 0.05           | 0.10         | 0.15         |
| 3      | d (mm)      | 0.25           | 0.40         | 0.55         |

On the basis of level and degrees of freedom (DOF) of the cutting parameters, Taguchi’s OA L9 has been chosen without any interaction effect for designing and running the experiment. Table 2 shows Taguchi’s OA L9 settings of the cutting parameters with their responses.

**Table 2. Taguchi’s OA L9 settings of the cutting parameters with responses.**

| Expt. No. | v (m/min) | d (mm/rev) | d (mm) | SR (µm) | FW (mm) | CF (N) |
|-----------|-----------|------------|--------|---------|---------|--------|
| 1         | 100       | 0.05       | 0.25   | 1.77    | 0.10    | 48     |
| 2         | 100       | 0.10       | 0.40   | 1.61    | 0.19    | 235    |
| 3         | 100       | 0.15       | 0.55   | 1.53    | 0.27    | 299    |
| 4         | 125       | 0.05       | 0.55   | 1.57    | 0.29    | 163    |
| 5         | 125       | 0.10       | 0.25   | 1.36    | 0.18    | 99     |
| 6         | 125       | 0.15       | 0.40   | 1.64    | 0.28    | 182    |
| 7         | 150       | 0.05       | 0.40   | 1.42    | 0.30    | 79     |
| 8         | 150       | 0.10       | 0.55   | 1.93    | 0.40    | 225    |
| 9         | 150       | 0.15       | 0.25   | 2.12    | 0.30    | 96     |

3.1. Grey relational analysis

Grey relational analysis is a statistical technique which is used for optimizing the multi-objective characteristics phenomenon. Multi-optimization technique is necessary and helpful in the sense that it selects single setting of the process parameters which give overall optimum values of various responses considered for the study. The first thing is to normalize the experimental data in between 0 and 1 and then the next step is to find the grey relational coefficient from the normalized experimental data in grey relational analysis. After finding the experimental coefficient for each response, the grey relational grade has been obtained for each experimental run. Finally, higher grey relational grade has been selected based on the higher value. Table 3 shows the normalized values of the responses viz. surface roughness, flank wear and cutting force as obtained from Table 2. The normalized data in Table 3 follows the pattern smaller the better criteria, i.e. smaller the values of responses, better will be their performances.

The grey relational formula for this is given by

\[
* x_i^*(j) = \frac{\max x_i(j) - x_i(j)}{\max x_i(j) - \min x_i(j)}
\]

Here, \(x_i^*(j)\) and \(x_i(j)\) are the sequences after the data processing and compatibility sequence respectively, \(j = 1\) for SR and \(i = 1, 2, 3, \ldots, 9\) for the nine experiments from 1 to 9. After finding the normalized value of the responses, the next step is to find the deviation sequences for each experimental run. This is found out by subtracting the value of each normalized term in the experimental run from the ideal reference value. Table 3 shows the deviation sequence for the responses of each experiment.
In the Table 3, $\Delta O_i (1)$, $\Delta O_i (2)$ and $\Delta O_i (3)$ represents the deviational sequences of the responses SR, FW and CF respectively.

$\Delta_{\text{max}} = \Delta O_i (1) = \Delta O_i (2) = \Delta O_i (3) = 1$, $\Delta_{\text{min}} = \Delta O_i (1) = \Delta O_i (2) = \Delta O_i (3) = 0$

$\Delta_{\text{max}}$ and $\Delta_{\text{min}}$ represents the maximum and minimum deviation of the above three responses respectively.

### Table 3. Normalized value of the responses SR, FW and CF and grey relational coefficient and grade

| Expt. No. | SR  | FW  | CF  | Deviation sequences | SR | FW | CF | Grey relational coefficient | Grey relational grade ($\gamma$) | Rank |
|-----------|-----|-----|-----|---------------------|----|----|----|-----------------------------|---------------------------|------|
| Reference Sequence | 1.00 | 1.00 | 1.00 | $\Delta O_i (1)$ | $\Delta O_i (2)$ | $\Delta O_i (3)$ | $\xi (1)$ | $\xi (2)$ | $\xi (3)$ | $\gamma$ | |
| 1         | 0.46 | 1   | 1   | 1                   | 0.54 | 0  | 0  | 0.48                         | 1                         | 1    | 0.826 | 2 |
| 2         | 0.67 | 0.7 | 0.25 | 2                   | 0.33 | 0.3 | 0.75 | 0.60                         | 0.62                       | 0.4  | 0.541 | 5 |
| 3         | 0.78 | 0.43| 0.0  | 3                   | 0.22 | 0.57 | 1  | 0.69                         | 0.47                       | 0.33 | 0.497 | 7 |
| 4         | 0.72 | 0.37| 0.54 | 4                   | 0.28 | 0.63 | 0.46 | 0.64                         | 0.44                       | 0.52 | 0.533 | 6 |
| 5         | 1    | 0.90| 0.79 | 5                   | 0    | 0.10 | 0.21 | 1                            | 0.83                       | 0.70 | 0.843 | 1 |
| 6         | 0.63 | 0.67| 0.47 | 6                   | 0.37 | 0.33 | 0.53 | 0.57                         | 0.60                       | 0.48 | 0.550 | 4 |
| 7         | 0.92 | 0.33| 0.87 | 7                   | 0.08 | 0.67 | 0.13 | 0.86                         | 0.42                       | 0.79 | 0.690 | 3 |
| 8         | 0.25 | 0.0 | 0.29 | 8                   | 0.75 | 1    | 0.71 | 0.4                           | 0.33                       | 0.41 | 0.380 | 9 |
| 9         | 0    | 0.33| 0.81 | 9                   | 1    | 0.67 | 0.19 | 0.33                         | 0.42                       | 0.72 | 0.491 | 8 |

3.1.1. Determination of grey relational coefficient and grey relational grade. Grey relational coefficient determines the values of the data after preprocessing. The grey relational coefficient correlates between the ideal and actual values of the normalized experimental data after the data preprocessing. The higher value of grey relational coefficient is an indication of better result as compared to lower value grey relational coefficient. The formula for finding the grey relational coefficient is given by

$$\xi_i (j) = \frac{\Delta_{\text{min}} + \zeta \Delta_{\text{max}}}{\Delta O_i (j) + \zeta \Delta_{\text{max}}}$$ (2)

Where $\Delta O_i (j)$ is the difference between the ideal sequence $x_o* (j)$ and the comparability sequence $x_i* (j)$ and $\zeta$ is the identification coefficient. For equal preference parameters $\zeta$ is taken as 0.5. The grey relational coefficient for all the nine experiments designed by Taguchi’s OA $L_9$ can be obtained by using the Eqn. (2) and the values are shown below in Table 3. After finding the grey relational coefficient for all the three responses, the grey relational grade has been found for each experimental run by taking the average values of all the grey relational coefficients for each experiment. The formula for finding the grey relational grade is given by

$$\gamma_i = \frac{1}{n} \sum_{j=1}^{n} \xi_i (j)$$ (3)

Here $\gamma_i$ denotes the grey relational grade for the $i^{th}$ experiment and $n$ denotes the number of responses. In Table 3, $\gamma$ represents the grey relational grade for each experiment, where, $\xi_i (j)$ represent the grey relational coefficients for $n$ responses. In Table 3, grey relational grade has been shown which is obtained from the average values of grey relational coefficients of the three responses for each experimental run. The higher value of grey relational grade has been found to be 0.843 and
chosen as rank 1 in the Expt. No. 5. As the design of the experiment is orthogonal, so the effect of all the cutting parameters in grey relational analysis can be considered by taking the average values of all the grey relational grade for each parameter level wise. Table 4 shows the average values of grey relational grade level wise for the three cutting parameters \( v \), \( f \) and \( d \) for the responses SR, FW and CF.

**Table 4.** Level wise average values of grey relational grade for SR, FW & CF in terms of cutting parameters

| SI No. | \( v \) (m/min) | \( f \) (mm/rev) | \( d \) (mm) | SR (µm) | Main effect (max-min) | Rank |
|--------|-----------------|-----------------|-------------|---------|----------------------|------|
| 2      | 0.621           | 0.683           | 0.720       | 0.520   | 0.122                | 3    |
| 3      | 0.642           | 0.568           | 0.593       | 0.512   | 0.171                | 2    |
| 4      | 0.642           | 0.568           | 0.593       | 0.512   | 0.171                | 2    |

Average value of grey relational grade = 0.594

In Table 4, the bold letter indicates the optimum value of the grey relational grade. From Table 4, it is observed that the optimum values of SR, FW and CF can be obtained at setting of \( v \) at level 2, \( f \) at level 1, and \( d \) at level 1. Again from Table 3, it is observed that the optimum values for SR, FW and CF can be obtained at a setting of \( v \) at level 2, \( f \) at level 2 and \( d \) at level 1 for Expt no. 5.

3.2. Confirmation test

The confirmation test for the setting \( v \) at level 2 = 125 m/min, \( f \) at level 1 = 0.05 mm/rev and \( d \) at level 1 = 0.25 mm has been performed according to the optimum grey relational grade from Table 4 and the corresponding response values of SR, FW and CF are found to be 1.30 µm, 0.15 mm and 84 N respectively. The estimated value of the grey relational grade \( \bar{\gamma} \) can be found using the formula

\[
\bar{\gamma} = \gamma_m + \frac{p}{\sum_{i=1}^{p} (\gamma_m - \gamma_i)}
\]  

(4)

So, from Table 5, it is confirmed that the grey relational grade is improved by 0.115. Comparing the settings of the Expt. No 5 and grey relational prediction it is observed that the surface roughness, flank wear and cutting force have been improved by 4.41%, 16.67% and 15.15% respectively. Hence grey relational prediction in machining AISI D2 steel using coated carbide tool has improved the machinability of AISI D2 steel. To confirm, which cutting parameters significantly affect the multiple-performance characteristics, analysis of variance (ANOVA) is also analyzed using the values of grey relational grades from Table 3. Table 6 shows the ANOVA for the grey relational grade.

**Table 5.** Grey relational grade improvement using the optimized machining parameters

| Condition | Expt no 5 in the OA L9 table | Using grey relational prediction |
|-----------|-------------------------------|---------------------------------|
| Level     | \( v_2-f_2-d_1 \)           | \( v_2-f_1-d_1 \)               |
| SR (µm)   | 1.36                          | 1.30                            |
| FW (mm)   | 0.18                          | 0.15                            |
| CF (N)    | 99                            | 84                              |
| Grey relational grade | 0.742 | 0.857 |

Grey relational grade improvement = 0.115
Table 6. ANOVA analysis of grey relational grade

| Parameters | Degrees of freedom (DOF) | Sum of square (SS) | Mean square (MS) | F-Ratio | Percentage contribution (%) |
|------------|--------------------------|--------------------|------------------|---------|-----------------------------|
| v (m/min)  | 2                        | 0.025              | 0.0125           | 0.641   | 12.51                       |
| f (mm/rev) | 2                        | 0.043              | 0.0215           | 1.10    | 21.52                       |
| d (mm)     | 2                        | 0.093              | 0.0465           | 2.38    | 46.54                       |
| Error      | 2                        | 0.039              | 0.0195           |         | 19.43                       |
| Total      | 8                        | 0.1998             |                  |         | 100                         |

From ANOVA in Table 6, it is confirmed that depth of cut is the most influencing parameter as compared to cutting speed and feed rate. This can be confirmed from Table 4 in which the main effect of grey relational grade of depth of cut is more as compared to cutting speed and feed rate.

4. Conclusion

In this work, an experimental study has been performed in machining AISI D2 steel using coated carbide tool in forced air-cooled environment. Taguchi’s OA L₉ and grey relational grade analysis have been performed for optimizing the multiple-performance characteristics of surface roughness, flank wear and cutting force. The outcome of the experimental results and grey relational analysis is summarized as follows:

The experimental results using grey relational analysis confirmed the optimum values of surface roughness, flank wear and cutting force in the Expt No 5 of Taguchi’s OA L₉. Grey relational prediction value confirmed the optimum values of surface roughness, flank wear and cutting force at a setting of cutting speed 125 m/min, feed rate 0.05 mm/rev and depth of cut 0.25 mm. Grey relational prediction value improved the responses surface roughness, flank wear and cutting force by 4.41%, 16.67% and 15.15% respectively as compared to the optimal settings of the machining parameters in the Expt. no 5. ANOVA analysis showed that the depth of cut is the most influential factor as compared to cutting speed and feed rate from the grey relational analysis.

References

[1] Bartarya G and Choudhury S K 2012 Int. J. Mach. Tools. Manuf. 53(1) 1-14
[2] Shao H, Li L, Liu L J and Zhang S Z 2013 J. Manuf. Process. 15(4) 673-81
[3] Strenkowski J S, Shih A J and Lin J c 2012 Int. J. Mach. Tools. Manuf. 42(6) 722-31
[4] Gopalsamy B M, Mondal B and Ghosh S 2009 Int. J. Adv. Manuf. Technol. 45 1068-1086
[5] Kacal A, Yildirim F 2012 J. Mech. Eng. Sci. 227 (7) 1566-76
[6] Huang J T and Liao Y S 2003 Int. J. Prod. Res. 41 (8) 1707-20
[7] Lin C L 2004 Mater. Manuf. Process. 19 (2) 209-20
[8] Nayak S K and Potro J K 2014 Proc. Mater. Sci. 6 701-08
[9] Mishra P C, Das D K, Ukamanal M, Routara B C and Sahoo A K 2015 Int. J. Eng. Comp. 6 445-56
[10] Sohrabpoor H, Khangah S P and Teimori R 2009 Int. J. Adv. Manuf. Technol. 76 (9-12) 2099-2116
[11] Patole P B, Kulkarni V V and Mang W 2017 Cog. Eng. 4(1) 1-14.