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Optimization of control parameters for mechanical and wear properties of carburized mild steel using grey relational analysis

Ravendra Singh*, Vedansh Chaturvedi, Jyoti Vimal*****
*Research Scholar, Department of Mechanical Engineering, Madhav Institute of Technology & Science Gwalior, INDIA
**Asst. Professor, Department of Mechanical Engineering, Madhav Institute of Technology & Science Gwalior, INDIA
***Asst. Professor, Department of Mechanical Engineering, Madhav Institute of Technology & Science Gwalior, INDIA

ABSTRACT
This paper presents the optimization of carburization process parameters for mild steel by using the Grey based Taguchi method. Design of experiments was done on the basis of an orthogonal array L_9 (3^4). Nine experiments were performed and mechanical & wear properties were selected as the quality target. An optimized parameter combination of the carburizing process was obtained via Grey relational analysis. By analyzing the Grey relational grade we find the degree of influence of each factor on the quality target. By this study we found that carburizing temperature was the most dominated factor, which mostly influences the mechanical and wear properties of carburized mild steel. At last, a confirmation test was conducted according to predicted optimal parameter setting and found the successful implementation of grey Taguchi approach.

Keywords: - **Carburized mild steel, Optimization, orthogonal-array, Grey relational analysis, Variance of analysis (ANOVA).**

1. INTRODUCTION
Carburization of mild steel involves a heat treatment of the metallic surface using a source of carbon. Early carburization used a direct application of charcoal packed onto the metal, but modern techniques apply carbon-bearing gases or plasmas (such as carbon dioxide or methane). The process depends primarily upon ambient gas composition and furnace temperature, which must be carefully controlled, as the heat may also impact the microstructure of the rest of the material.

For the optimal selection of process parameters, the Taguchi method has been extensively adopted in manufacturing to improve processes with single performance characteristic. However, traditional Taguchi method cannot solve multi-objective optimization problem. To overcome this, the Taguchi method coupled with Grey relational analysis has a wide area of application in manufacturing processes [1– 6]. This approach can solve multi-response optimization problem simultaneously [7].

Deng (1982) proposed grey relational analysis to fulfill the crucial mathematical criteria for dealing with a poor, incomplete, and uncertain system [10]. Besides that, it is an effective method for optimizing the complicated inter-relationships among multiple responses [8-11]. The theories of grey relational analysis have already attracted much interest among researchers [12-14]. Planning the experiments through the Grey Taguchi orthogonal array has been used quite successfully in process optimization by Lin and Lin [15], Lung et al [16], Chorng et al [17], Li et al [18], Tsai et al [19], Ko. et al [20] and Yu. et al [21].

By using this method, complicated multiple responses can be converted into normalized response known as Grey Relational Coefficient (GRC). The Grey-Taguchi method which is a combination of Taguchi method and GRA will enhance better response of complicated problems in manufacturing process [22].

Grey relational analysis was performed to combine the multiple responses into one numerical score, rank these scores, and determine the optimal carburizing parameter settings. Confirmation tests were performed by using experiments. ANOVA also performed to investigate the more influencing parameters on mechanical and wear properties [23].

2. METHODOLOGY
Here Grey based Taguchi method applied for finding most significant factor, which influences the mechanical and wear properties of carburized mild steel. The structure of Grey based Taguchi method shown in figure 1. There were three steps involved; in first step we designed the experimental runs with the help of orthogonal array L_9. In second step Grey based Taguchi method was applied and analyzing the most effective process parameters with the help of Grey relational coefficients & Grey relational grade. At the last step ANOVA analysis applied and found most significant parameter.

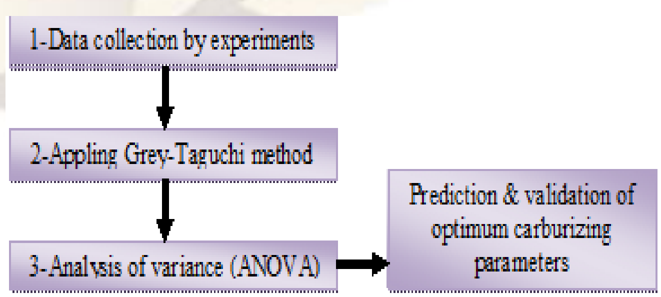


Figure 1. Structure of Grey based Taguchi Method

2.1- Grey-Relational Analysis

Grey data processing must be performed before Grey correlation coefficients can be calculated. A series of various units must be transformed to be dimensionless. Usually, each series is normalized by dividing the data in the original series by their average. Let the original reference sequence and sequence for comparison be represented as xo(k) and xi(k), i=1, 2, . . .,m; k=1,2, . . ., n, respectively, where m is the total number of experiment to be considered, and n is the total number of observation data. Data preprocessing converts the original sequence to a comparable sequence. Several methodologies of preprocessing data can be used in Grey relation analysis, depending on the characteristics of the original sequence [10][24][25].

If the target value of the original sequence is "the-larger-the-better", then the original sequence is normalized as follows.

$$x_i^*(k) = \frac{x_i^{(o)}(k) - min.\ x_i^{(o)}(k)}{max.\ x_i^{(o)}(k) - min.\ x_i^{(o)}(k)} \qquad (1)$$

If the purpose is "the-smaller-the-better", then the original sequence is normalized as follows.

\

$$x_i^*(k) = \frac{max.\ x_i^{(o)}(k) - x_i^{(o)}(k)}{max.\ x_i^{(o)}(k) - min.\ x_i^{(o)}(k)} \qquad (2)$$

However, if there is "a specific target value", then the original sequence is normalized using,

$$x_i^*(k) = 1 - \frac{x_i^{(o)}(k) - OB}{max.\ \{max.\ x_i^{(o)}(k) - OB, OB - min.\ x_i^{(o)}(k)\}} \qquad (3)$$

Where, OB is the target value.

Alternatively, the original sequence can be normalized using the simplest methodology that is the values of the original sequence can be divided by the first value of the sequence, $x_i^{(o)}(1)$.

$$x_i^*(k) = \frac{x_i^{(o)}(k)}{x_i^{(o)}(1)} \qquad (4)$$

Where, $x_i^{(o)}(k)$ is the original sequence, $x_i^*(k)$, the sequence after data preprocessing, max, $x_i^{(o)}(k)$, the largest value of , $x_i^{(o)}(k)$ and min , $x_i^{(o)}(k)$, the smallest value of , $x_i^{(o)}(k)$.

Grey Relational Coefficients and Grey Relational Grades:

The Grey relational coefficient is defined as follows.

$$\gamma\{x_0^*(k)\ .x_i^*(k)\} = \frac{\Delta_{min.} - \zeta.\Delta_{max.}}{\Delta_{0i}(k) - \zeta.\Delta_{max.}} \qquad 0 \le \zeta \le 1 \qquad (5)$$

$$0 < \gamma\{x_0^*(k)\ .x_i^*(k)\} \le 1$$

$\Delta_{0i}(k)$ is the deviation sequence of reference sequence $x_0^*(k)$ and $x_i^*(k)$ namely,

$$\Delta_{0i}(k) = \quad |x_0^*(k) - x_i^*(k)|$$

$$\Delta_{max.} = \underset{\forall j \in i}{max.}\ \underset{\forall k}{max.}\ |x_0^*(k) - x_j^*(k)|$$

$$\Delta_{min.} = \underset{\forall j \in i}{min.}\ \underset{\forall k}{min.}\ |x_0^*(k) - x_j^*(k)|$$

A Grey relational grade is a weighted sum of the Grey Relational Coefficients, and is defined as follows,

$$\gamma(x_0^*, x_i^*) = \frac{1}{n}\sum_{k=1}^{n} \beta_k \gamma\ \{x_0^*(k), x_i^*(k)\}$$

$$\sum_{k=1}^{n} \beta_k = 1 \qquad (6)$$

Here, the Grey relational grade $\gamma(x_0^*, x_i^*)$ represents the level of correlation between the reference and comparability sequences. If the two sequences are identical, then the value of the Grey relational grade equals to one. The Grey relational grade also indicates the degree of influence exerted by the comparability sequence on the reference sequence. Consequently, if a particular comparability sequence is more important to the reference sequence than other comparability sequences, the Grey relational grade for that comparability sequence and the reference sequence will exceed that for other Grey relational grades. The Grey relational analysis is actually a measurement of the absolute value of data difference between the sequences, and can be used to approximate the correlation between the sequences.

3. EXPERIMENTAL DATA

Table 1. Experimental factor and factor levels

Control Variable	Code	Level			Observed values
		1	2	3	
Carburization Temperature (^oC)	A	820	890	960	1- Hardness (Rc)
Carburization Sock Time (hr)	B	2	3	4	2- Toughness (J)
Tempering Temperature (^oC)	C	210	260	320	3- Tensile Strength (MPa)
Tempering Sock Time (hr)	D	0.6	1.1	1.5	4- Wear Rate (cm^2x10^{-7})

Table 2. Experimental results of carburized mild steel

Run No	A	B	C	D	Hardness	Toughness	Tensile strength	Wear rate
1	1	1	1	1	52.00	35.00	453.50	4.88
2	1	2	2	2	53.00	34.50	692.50	4.91
3	1	3	3	3	51.50	35.50	685.00	4.56
4	2	1	2	3	54.00	36.00	1061.0	3.43
5	2	2	3	1	53.00	33.50	1395.5	3.63
6	2	3	1	2	55.50	34.00	1287.0	3.35
7	3	1	3	2	58.50	33.00	1682.5	2.42
8	3	2	1	3	55.00	32.50	1910.0	2.56
9	3	3	2	1	59.50	33.50	1897.5	2.40

Table 3. Grey relational generation of each performance characteristics

Comparability Sequence	Larger-the-better			Smaller-the-better
	Hardness	Toughness	Tensile strength	Wear rate
No. 1	0.063	0.069	0.000	0.01
No. 2	0.188	0.571	0.164	0.00
No. 3	0.000	0.857	0.159	0.14
No. 4	0.313	1.000	0.417	0.59
No. 5	0.188	0.286	0.647	0.51
No. 6	0.500	0.429	0.572	0.62
No. 7	0.875	0.143	0.844	0.99
No. 8	0.438	0.000	1.000	0.94
No. 9	1.000	0.286	0.991	1.00

Table 4. Evaluation of Δ_{0i} for each of the responses

Comparability Sequence	Hardness	Toughness	Tensile strength	Wear rate
No. 1	0.938	0.931	1.000	0.988
No. 2	0.813	0.429	0.836	1.000
No. 3	1.000	0.143	0.841	0.861
No. 4	0.688	0.000	0.583	0.410
No. 5	0.813	0.714	0.353	0.490
No. 6	0.500	0.571	0.428	0.378
No. 7	0.125	0.857	0.156	0.008
No. 8	0.563	1.000	0.000	0.064
No. 9	0.000	0.714	0.009	0.000

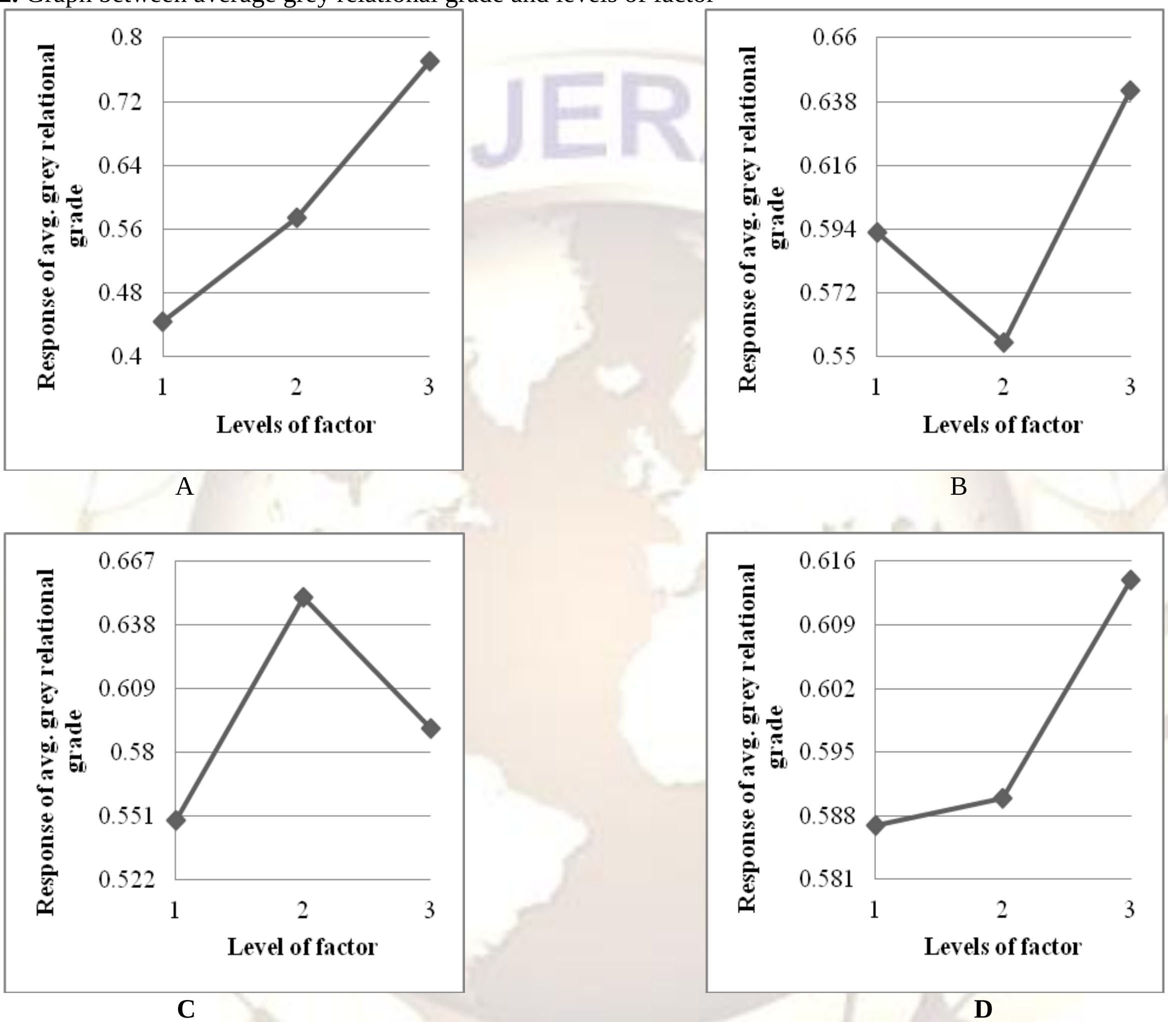
Table 5. Evaluated Grey relational coefficients and Grey relational Grades for 9 groups

Exp no.	Orthogonal array				Grey- relational coefficient [Distinguishing Coefficient ζ=0.60]				Grey-relational grade
	A	B	C	D	Hardness	Toughness	Tensile strength	Wear rate	
1	1	1	1	1	0.390	0.392	0.375	0.378	0.384
2	1	2	2	2	0.425	0.583	0.418	0.375	0.450
3	1	3	3	3	0.375	0.808	0.416	0.411	0.502
4	2	1	2	3	0.466	1.000	0.507	0.594	0.642
5	2	2	3	1	0.425	0.457	0.629	0.550	0.515
6	2	3	1	2	0.545	0.512	0.584	0.613	0.564
7	3	1	3	2	0.828	0.412	0.793	0.987	0.755
8	3	2	1	3	0.516	0.375	1.000	0.904	0.699
9	3	3	2	1	1.000	0.457	0.986	1.000	0.861
									5.372

Table 6. Calculate Average Grey relational grades

Level	Factors			
	A	B	C	D
1	0.445	0.593	0.549	0.587
2	0.574	0.555	0.651	0.590
3	0.771	0.642	0.591	0.614

Figure 2. Graph between average grey relational grade and levels of factor



4. ANALYSIS OF VARIANCE (ANOVA): ANOVA analysis using the calculated values from the Grey relational grade from Table 5 and the Table 6.

Table 7. ANOVA analysis for hardness, toughness, tensile strength and wear rate

Factors	Level			D O F	Sum Of Square	Mean Square	F-Value	SS'	Contribution (%)
	1	2	3						
A	0.445	0.574	0.771	2	0.162	0.081	0.081	0.162	84.921
B	0.593	0.555	0.642	2	0.012	0.006	0.006	0.012	6.051
C	0.549	0.651	0.591	2	0.016	0.008	0.008	0.016	8.297
D	0.587	0.59	0.614	2	0.001	0.001	0.001	0.001	0.731
Error				0	1.975	0			
Total				8	0.191	0.095		0.191	100

By above mathematical treatment Table 7 shows that the factor A, Carburization temperature with 84.92% of contribution, is the most significant factor for carburization process of mild steel, the carburization sock time is with 6.05% contribution, the tempering temperature with 8.29%, and tempering sock time with 0.73% of contribution if the maximization of Hardness, Toughness, and Tensile strength and the minimization of wear rate are considered simultaneously.

5. CONFIRMATION TEST

After identifying the optimal level of the process parameters, the final step is to predict and verify the improvement in the responses using the optimal process parameters. The $A_3B_3C_2D_3$ is an optimal process parameters combination for the carburization process. So this $A_3B_3C_2D_{13}$ optimal parameters combination was used for confirmation test. Confirmation test shows that if optimal setting with a carburization temperature 960 ^{0}C, carburization sock time 4 hr., tempering temperature 260 ^{0}C, tempering sock time 0.6 hr., the final results obtained as hardness 60.34 Rc, toughness 37 J, tensile strength 1980 MPa, and wear rate 1.80 cm^2 $x10^{-7}$. It is clearly shows that the Grey based Taguchi method improve the multi responses in carburization process for mild steel.

6. CONCLUSIONS

Designed experiments were conducted on muffle furnace with mild steel as work piece to optimize the carburization parameters. By above mathematical treatment different results are summarized given below:

- From table 6 shows that the largest value of average Grey relational grade for carburization temperature of 960 ^{0}C, carburization sock time of 4 hr., tempering temperature of 260 ^{0}C, and tempering sock time of 0.6 hr. These are the effective control parameters which are used for carburization process to minimization of wear rate and maximization of hardness; toughness & tensile strength are simultaneously considered.
- From ANOVA analysis table 7 shows that the carburization temperature is most significant factor for carburization process.
- The confirmation result shows that the sequence of identified optimal parameters is suitable for carburization process of mild steel.

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