Multiple Performance Optimization of Carburized Steel Using Taguchi Based Moora Approach

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Abstract- *In this research, a multi-response optimization based on Taguchi method-based MOORA (Multi-response optimization based on ratio analysis) is proposed for carburization process of low carbon steel. Experiments were designed using (Taguchi's) method with six input carburization factors (carburization temperature, carburization time, tempering temperature, tempering time, activator wt.%, and quench media). Depth case and wear rate were considered as the most response measures in this study. Results of the analysis shows that the carburization temperature is the most significant variables for the optimum outcome results. The desired response measures and mathematical model were achieved and used as optimum condition tool. The outcome of this study had been explored the possible use of the developed carburized steel in high wear resistance applications.*

Keywords- *ANOVA, carburization, Multi-objective optimization MOORA, Taguchi approach.*

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1. Introduction

Carburization can be considered as one of the oldest heat treatments, which used for surface treatment hardening. This process was developed for further improvement of the mechanical properties of the work piece in particular the cutting tools. The purpose of this technique is to enhance the hardness and wear resistance of the outer layer by increasing the case with higher rate of carbon with subsequent quenching without effecting on the core properties [1]. Low carbon steel (0.1 to 0.1 % C) is usually not respond to direct hardening, but will respond to surface hardening such as carburizing. Carburizing is the modification of specimen surface by the addition of carbon at temperatures range of the certain steel, which usually is between (850-950 oC). In this range, the austenite is the more stable phase. Quenching is used when the subsequent rich carbon surface layer is hardening to form the hard phase (martensite), so that rich carbon martensite case and improvements in hardness and wear resistance is combined with a tough core. The diffusivity of carbon in austenite is affected by both the carbon concentration and the carbon temperature, thus the case thickness and the carbon distribution in the diffusion zone depends on the carburization parameters. Many researchers have been studied the process parameters in metals quenching for some years [2,3]. Carburizing is referred to a thermo-chemical operation of diffusion enriching the surface with carbon. Saturation with carbon atoms is to improve the wear strength and hardness [4]. The wear resistance of steel substrate can be increased by surface heat treatment. This technique provides a combination between the hard case and the soft core. The high value of surface hardening has a major effect on the increasing of value of wear resistance and hence, improves the performance of the part during surface life. Carburizing is one of the well-known used surface hardening techniques, which has the minimum value of thermal distortion. The carburized layer obtained by this process is controlled by the carburization parameters [5,6]. Many studies find out that the effect of the controllable of carburization parameters [7-10], and carburizing technique was revealed to increase the hardness and wear resistance [11-18], and steel corrosion resistance [19,20]. Most researchers find out the influences of carburization parameters like: (carburizing temperature, soaking time, quenching method, and tempering temperature). Carburizing temperature and soaking time effects on the hardness value and case depth of steel [21,25]. In order to select the carburization parameters, the (Taguchi) principle has been widely used in carburization process to enhance processes with single output. However, (Taguchi) principle cannot process multi-output optimization problems. Avoiding such problem can be done by using the (Taguchi) principle combined with (MOORA) which has a wide range of applications in carburization processes [25]. This

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method can solve multi-response optimization in combined with (Taguchi) method. Designing of the experiments through the (MOORA- Taguchi) orthogonal array has been used successfully in the processes of optimization. By using this approach, multiple responses (case depth and wear rate) can be converted into single response. The (MOORA – based Taguchi) approach will led to better response of complex problems in carburization process [26]. MOORA analysis was carried to combine the multiple responses into single response, rank these scores and determine the optimal carburizing parameter settings. Analysis of variance (ANOVA) also determined to evaluate the more influencing parameters on multiple response properties. In this research, an effort has been taken to improve the performance of wear behavior for carburized steel by (Taguchi) based (MOORA) approach and an experimental research on effects of carburization parameters have been performed. Regression analysis have also been used for optimum performance characteristics.

2. MOORA Approach

Multi or several objective optimizations, which is also known as (multi-attribute optimization), can be defined as the simultaneously optimizing process for more than two conflicting attributes related to certain conditions. The (MOORA) approach was represented for the first time by "Brauers" in the year (2004) whom describe it as a technique that can be successfully used to solve various types of complex decision making problems for many applications by using multi-objective methods. The (MOORA) approach starts with a decision matrix: [27].

D =

$$\begin{array}{c|ccccc|} & C_1 & C_2 & C_3 & \cdots & C_n \\ A_1 & X_{11} & X_{12} & X_{13} & \cdots & X_{1n} \\ A_2 & X_{21} & X_{22} & X_{23} & \cdots & X_{2n} \\ A_3 & X_{31} & X_{32} & X_{33} & \cdots & X_{3n} \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ A_n & X_{m1} & X_{m2} & X_{m3} & \cdots & X_{mn} \end{array}$$

In this step, based on the available information about the alternatives, decision-making matrix or decision table is set. Each row refers to one alternative, and each column to one criterion, where (D) refer to the initial decision matrix. The steps of (MOORA) for ranking alternatives follows:

Step 1: Determining of the normalized (MOORA) matrix, which defined by equation (1) as illustrated below:

$$X'_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{m} X_{ij}^2}} \quad (1)$$

Where $i = 1 \ldots . m; j = 1 \ldots . . n$

Step 2: Determine the attributed degree using equation (2) below:

$$Z_i = \sum_{j=1}^{b} X'_{ij} - \sum_{j=b+1}^{n} X'_{ij} \; ; \quad (2)$$

where $i = 1, . . , m$

Where: $\sum_{j=1}^{b} X'_{ij}$ and $\sum_{j=b+1}^{n} X'_{ij}$ are positive and negative criteria, respectively and if there are attributes more important than others, the attributed degree of these attributes become as mensioned in equation (3) below:

$$Z_i = \sum_{j=1}^{b} W_j X'_{ij} - \sum_{j=b+1}^{n} W_j X'_{ij} \quad (3)$$

Where: W_j is the weight of (j^{th}) criteria, $i = 1, 2, .., m$.

Step 3: Arrangement the outputs in descending order to determine the ranking of them. Figure 1 shows the block diagram of (MOORA) approach.

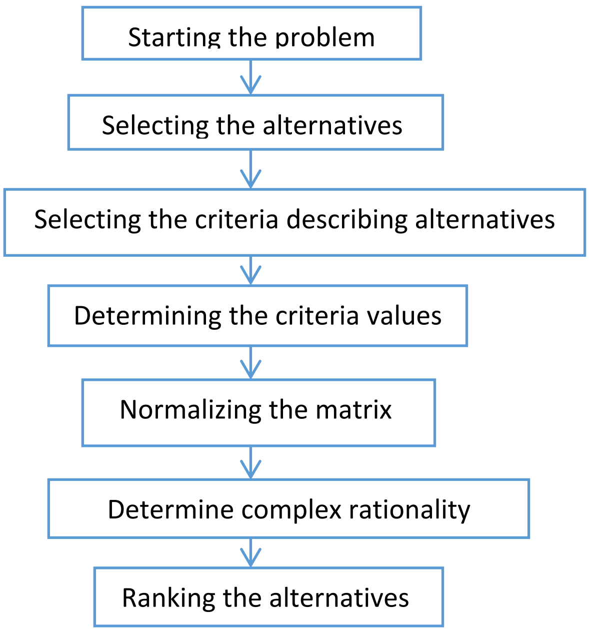

Figure 1: Sequence of operations in (MOORA) approach.

3. The Taguchi Method

The Taguchi principle is most important method as compared with the other experimenal designs methods. Most limitations of this method is used for one single response only. Only main the control factors and the interactions between them are considered. Taguchi principle is as following:

- Performence should be specified according to objective value.
- Performence must be adopted through suitable design of the (Taguchi array).

In general, the Taguchi principle include, two important factors: (the control factor) and (the noise factor) which are usually used to study the effect of responses. The input factors are used to select the aproperate conditions for a carburization process, whereas the noise parameters denote, all parameters that cause negative effects. The (Signal-to-Noise (S/N)) ratio is determined to obtain the desired set of input factors. Usually, the (S/N) ratio is determining for evaluating the single and multiple effect of the parameters and the maximum value can be used as the optimum value. According to the quality outcomes, the (Taguchi) principle is divided into three major parts:

- The (Nominal-the-Better (NB)),
- The (Larger-the-Better (LB)),
- The (Smaller-the-Better (SB)).

In the following (Larger - the - Better (LB)) method is used in order to determine the higher response functions. The (S/N) ratio can be calculated as follows [28]:

$$SN_i = -10\log\left(\frac{1}{N_i}\sum_{k=1}^{N_i}\frac{1}{y_k^2}\right) \quad (4)$$

Where: i, k, N_i stand for (number of experiments), (number of trials) and (total number of experiments), respectively.

4. Analysis of Variance (ANOVA)

The main objective of (Analysis of Variance-ANOVA) is to determine which (carburization factors) significantly affect the quality characteristic [29]. This is can be carried out by separating the total variations of the positive attributes, which is determined by the summation of the squared deviations from the total average of the positive attributes, into contribution percentage by each (carburization factors) and the error. Thus:

$$SS_T = SS_F + SS_e \quad (5)$$

Where:

$$SS_T = \sum_{j=1}^{p}(\gamma_j - \gamma_m)^2 \quad (6)$$

Where:

SS_T: Total summation of squared deviations about the average.

γ_j : Average response for the (j^{th}) experiment.

γ_m : Total average of the response.

p : Number of experiments in the (Taguchi) array.

SS_F: Summation of squared deviations due to each parameter.

SS_e : Summation of squared deviations due to error.

5. Experimental Procedure

The composition of (SAE1/1012) steel reported in this work is listed in Table 1 and the quenching media used in this study are listed in Table 2. The specimens of (low carbon steel) were cleaned with alcohol (CH_3COCH_3) in order to remove the impurity. The samples then were subjected to pack carburization treatment using a carburizing box. This box was packed with a carburizing (Graphite) with appropriate activator particles ($BaCO_3$). The volume fractions were (90% of graphite & 10% of activator). After that, a clay cover was used to seal the carburizing box very tightly; this was done to prevent all kinds of undesired gases from the furnace to inter the carburizing box while the specimens were heated. The temperatures of heating furnace were regularizing according to (Taguchi) array for the carburization operations. The carburizing box, which contains the specimens, was placed in the furnace in these three different temperatures. After reaching each separated temperature, which refer to the required heat treatment temperature, soaking operation at each separated temperature were done using (Taguchi) array. Specimens inside the box were held for the required hours then the steel carburizing container was transferred from the furnace and opened to get the specimens from it, which were quenched, in quenching media. The carburized steel specimens were then subjected to tempering for a specified temperature and time and then it processed for the wear test. The depth of carburized layer was microscopically determined after polishing then etching the samples by (Natal) solution (2% nitric acid in alcohol). The sample preparation for microstructure examination is done by traditional method which is consist of grinding and polishing using (silicon carbides SiC) (320, 400, 600, 800, 1000 and 1200) followed by etching process by using Nital (2% nitric acid & 98% alcohol).

Table 1: Chemical Composition of (SAE1/1012)

Element	C %	Si %	Mn %	P %	S %	Mo %	Ni %	Al %	Co %
Weight%	0.122	0.0005	0.442	0.0005	0.0269	0.001	0.0119	0.0052	0.001
Element	Cu %	Cr %	Fe						
Weight%	0.0135	0.0097	Bal.						

Table 2: Quenching Media.

Quenching media	Approximate composition
Brine	Aqueous solution, (10 wt.%) NaOH.
Polymer	Polyvinyl alcohol, (92 wt.%) water.

The carburized and tempered (low carbon steel) specimens were then examined using abrasive wear tests. An abrasion test specimen was done according (ASTM) standards and the standard specimen dimensions were (4cm×2.5cm×0.5cm) of steel is prepared in order to study the hardness characteristics of each the carburized specimens. The test was done on a machine called (pin on disc). Since the (weight loss) was determined so it was converted to (volume loss) using the (density) of the specimen. Hence (wear volume) and (wear rate) were calculated as:

$$\text{Wear volume}=\frac{\text{weight loss}}{\text{density}} \quad (7)$$

Density of specimen = 7.86 (g/cm^3)

$$\text{Wear rate}=\frac{\text{wear volume}}{\text{sliding distance}} \quad (8)$$

$$\text{Sliding distance} = V * \text{time}= \frac{2\pi RN}{60} * \text{time} \quad (9)$$

R = radius of abrasive wheel = 6 (cm).

N = r.p.m (900)

Time = 10 minutes (600 sec).

The amount of load applied is (30 N) according to [11].

In this research, the experimental work was done according to (Taguchi) array. With respect to the experimental conditions, the number of level and carburization parameters are given in Table 3, where (Taguchi) method, (L_9) array was employed.

The (S/N) quantitative relation for wear resistance can be calculated as (the Larger - the better) rule as portrayed within the following equation:

$$\text{SN}= -\log\left(\sum \frac{y_i^2}{n}\right) \quad (10)$$

Where, (n) refer to the orthogonal array number of experiments and (yi) is the (i^{th}) value measured. The corresponding (OA) according to level numbers of carburization parameters that will be used in the experiments. Table 4 shows (L_9-Taguchi) array from Table 3. The depth of carburized material depends on time, temperature and quench media where detailed plan of work is shown in the Table 4 below.

Table 3: Level numbers of carburization parameters.

Factor	Factor code	Levels		
		1	2	3
Carburization Temperature. (^{o}C)	A	850	900	950
Carburization time (hrs.)	B	2	4	6
Tempering temperature (^{o}C)	C	200	250	300
Tempering time	D	1	1.5	2
Activator wt.%	E	10	10	10
Quench Media	F	Water	Brine	Polyvinyl alcohol

Table 4: The (L9) orthogonal array.

No. of Exp.	Activator wt.%	Carburized Temperature (^{o} C)	Carburized Time (hrs.)	Quench. media	Tempering Temperature	Tempering Time (hrs.)
1	10	850	2	Water	200	1
2	10	850	2	Water	250	1.5
3	10	850	2	Water	300	2
4	10	900	4	Brine	200	1
5	10	900	4	Brine	250	1.5
6	10	900	4	Brine	300	2
7	10	950	6	Polymer	200	1
8	10	950	6	Polymer	250	1.5
9	10	950	6	Polymer	300	2

6. Results and Discussion

The experimental results were collected for case depth and wear rate then they were analyzed by (MOORA) method as shown in Table 5. The (MOORA) or decision matrix includes the measured responses (i.e. case depth and wear rate). Each values of measured performance. Normalized value of (X_{ij}) can refers to the assessment for (i^{th}) substitute compared to all attributes using Eq.(1) . In order to optimize the measured response, the control parameters are either added for maximum positive attributes or subtracted for minimum negative attributes, as shown in Eq. (2). Thus, the best alternative has the highest beneficial attributes value, while the worst alternative has the lowest beneficial attributes, the depth case considered as beneficial attribute (i.e. higher values are desirable), wear rate is considered as non-beneficial attribute (i.e. lower values are desirable). It is very difficult to predict the exact relationship between the case depth and its effects on the wear rate for the specimens, so, each response is assigned with equal weight of ($W_j = 1$) using Eq.(3), (i.e. each response is important with the same weight). The ranking of each experimental set is also shown in Table 5 using (MOORA) approach. It can be observed that the experiment number (1) has the maximum normalized multi-response value, with the high value depth case and lowest value of wear rate. Table 5 shows that the (MOORA) approach for (carburization parameter) selection problem which suggests that optimal (carburization parameters) are: (activator wt.%:10, carburizing temperature ^{o} C): 850, carburizing time (hrs.): 2, quenching media: water, tempering temperature (^{o}C): 200, tempering time (hrs.): 1.).

ANOVA was used to determine the effect of control parameters and to determine the percentage contribution of each parameter. The mean effect of the main factors on positive attributes is given below. ANOVA table (showed in Table 3) shows that the (carburizing temperature (49 %)) have a significant effect on the positive attributes. Further results reveals that the percentage contributions of (activator (wt.%) is (44 %)), (tempering time (7 %)), (quench media (0 %)) and tempering temperature (0 %)). The expected error is (2 %). The relationship between the factors (carburization temperature, carburization time, tempering time, activator (wt.%) and quench media) and the performance measures (beneficial attributes for wear rate and case depth) were modeled by multiple linear regression. The following equation is the final models in terms of carburization parameters. The (R^2) value of regression model for objective function shown below shows that the predicted results (87.41 %) of the variance in positive attributes. The adjusted (r-squared (R^2)) is (85.90 %), which explained the number of predictors in the model. Both values indicate that the model fits the reference data well.

Table 5: Results of multi-objective analysis.

Exp. No.	Case depth (mm)	Wear Rate ($cm^2 \times 10^{-7}$)	Normalization		Beneficial attributes	MOORA Rank
			Depth Penetration	Wear Rate		
1	7.4628	1.733	71.54	11.50	0.60	1
2	5.857	1.811	37.40	25.09	0.12	5
3	5.5408	1.824	33.80	27.42	0.06	9
4	5.5408	2.662	33.80	26.73	0.07	8
5	4.4938	2.788	37.77	28.24	0.10	6
6	4.646	2.798	36.53	27.92	0.09	7
7	7.4448	3.342	58.53	26.40	0.32	3
8	8.242	3.351	71.03	26.42	0.45	2
9	6.96	3.876	51.54	27.46	0.24	4

7. Structure and phase composition of carburized layers

Figure 1 shows the microstructure of the carburized layer of specimen treated according to (Taguchi) design array. Metallography was examined by using an optical microscope with an image processing computerized camera. Figure 1 illustrate microstructures of cross section area for carburized specimen according to Taguchi array. Differences in the penetration depth of all samples with the different tests had been noticed. These tests refer to microstructures changes from the surface of low carbon steel to the core after carburized, quenched and tempering. The case with dark like structure is martensite. Between case and core are martensite and ferrite. It has been observed that variety of penetration depth in Figure 1 and this may due to different parameter combination of carburization as indicated in each run of (Taguchi) array. The significant increase of the case depth thickness is noticeable, and thus, exhibits good wear resistance, shows that none of the tests reached the substrate, (i.e. the obtained wear resistance is directly related to the carburized layers formed by the carburization). The phases usually obtained in carburizing are confirmed by X-ray diffraction (XRD) analysis. The carburized samples were characterized with (X-ray) diffraction in order to characterize the phases that have developed in the carburized layer. Figure 2 present (X-ray) diffraction patterns of carburized steel at optimum conditions i.e. activator wt.%:10, carburizing temperature ° C): 850, carburizing time (hrs.): 2, quenching media: water, tempering temperature (° C): 200, tempering time (hrs.): 1. The (X-ray) diffraction pattern for steel carburized at (870 °C) shows that several iron carbides phase of (Fe3C) and (Fe3C2), have formed during this treatment. During carburizing at austenitic temperature the steel substrates is converted into carbon rich martensite. The diffusion of carbon interstitial atoms produces a distorted structure which causes the precipitation of iron carbides phases. Theses iron carbides phase were restructured when carburizing temperature was increased, this is in good agreement with [1].

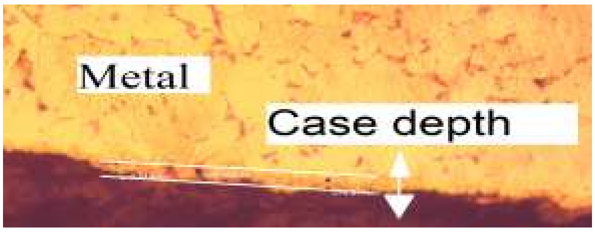

Figure 1: Micrograph and case depth of carburized steel according to (Taguchi) array (1000x).

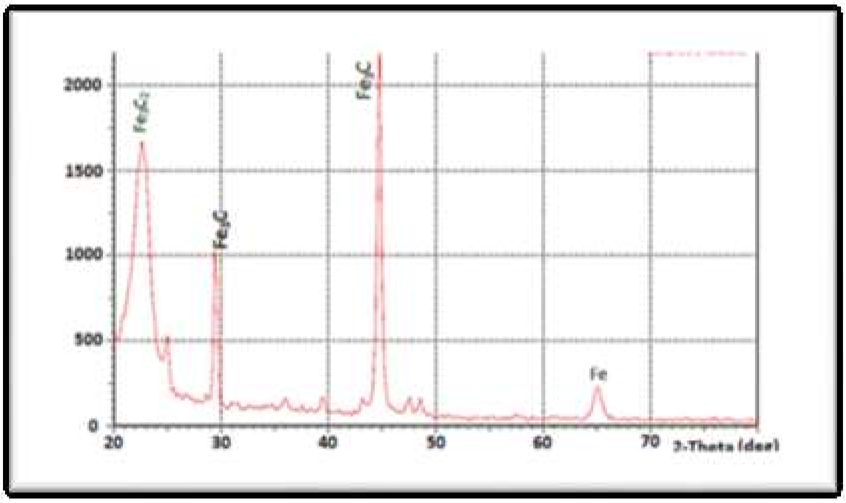

Figure 2: Diffraction spectra of steel carburized at optimum conditions.

8. Conclusions

This work includes the using of (MOORA) approach in determining of optimized (carburization process) parameters for (carburized low carbon steel). This multi-response optimization method uses a ranking principle for the determination of (carburization parameters). From results, it was concluded that the optimization of (carburization parameters) are in good agreement with the results obtained in literature. It is thereby concluded that (MOORA) method has successfully optimized the (carburization parameters) considered in this research. The characterization using both the microstructure and (X-ray) diffraction of the carburized (low carbon steel) specimens obtained by the optimized process parameters showed that good quality of the response characteristics (i.e. case depth and wear resistance). The characterization of the microstructure confirms that the carburized specimens produced by the optimized (carburization parameters) are of excellent (wear resistance) and (case depth).

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