Modeling of Carburization Parameters Process for Low Carbon Steel

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ABSTRACT:

This paper represents the carburization parameters for steel (1020) using Desirability Function Analysis-DFA. The experiments were conducted using Taguchi (L_9) orthogonal array. Carburization parameters such as carburization temperature, carburization time and tempering temperature were optimized by multi - response considerations depending on micro hardness and were rate measurements. The optimal carburizing parameters had been determined by composite desirability value obtained from desirability function analysis while significant contribution of parameter was determined by analysis of variance (ANOVA). The analyses results showed that optimal combination for higher hardness and lower wear rate were at (A2=920 ^{o}C, B2= 3 hours and C3=120 ^{o}C). Confirmation test was also conducted to validate the test results. Mathematical models for composite desirability, micro hardness and rate wear were determined. Experimental results showed that the carburization performance can be improved effectively through desirability approach.

Keywords: Taguchi, ANOVA, carburization temperature, carburization time, tempering temperature.

INTRODUCTION:

One of the most important groups of engineering materials is steels which represent the widest applications in materials engineering. There are many types of steels, each of them was designed to a particular application in engineering fields [1]. Recently, the researchers were very interested in surface engineering of the steels to improve the life and performance of products which may be used in automobiles and aerospace [2].

Several techniques like thermochemical treatments have been well studied and were widely used in the industry to improve products life. In this method, the metals or non-metals will be modified and a chemical reaction is followed into the surfacethe composition of product surface, the structure of product surface and the properties of product surface will be changed at the end of the thermochemical treatments. Carburizing, nitriding, aluminizing, chromizing and carbonitriding are the most popular methods for industrial applications [3]. Carburizing is a thermochemical process which is used to increase the resistance ofproducts surface wear and hardness [4].Carburizing is the operation of adding carbon to the surface of low carbon steel at temperatures of austenitic region,

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this operation usually is done at (850-950^{o}C),On such range of temperatures, there will be a high solubility of carbon which had stable crystal structure. So, a tough low carbon steel core can be produced with good hardness and wear resistance when a high carbon surface layer quenched to form martensite hardening [5].

Usually carbon diffusion rate depends on: steel chemical composition, carburization temperature and chemical composition of the carburizing mixture [6]. The successful of carburizing operation can be done when a control on three factors is achieved, these factors are the temperature of carburizing, the time of carburizing and chemical composition [7].

In this research, Taguchi approach was used which is a powerful statistical tool had multi statistical techniques and abilities of joining and interact with multiple processes variables identifications based on a few experiments. This approach is widely used because of its efficiency in optimize the operational variables for experimental design [8].The two major tools used in Taguchi method are orthogonal array (OA) and the signal to noise ratio (S/N) ratio. Taguchi's method, in general provide a significant reduction in the size of experiments which can provide speeding up the experimental processes [9].

This research focuses on the carburizing process parameters optimization of the (low carbon steel) specimens by (Taguchi's-(L_9)) orthogonal array concept and thereby determining the optimum values which will maximize the hardness valueand minimize the wear rate.In general there are many approaches to solve the optimization problem like genetic algorithm, response surface, factorial design and Taguchi approach which is considered the most stable, as it reduce the number of experiments. Improvement in computer technology made it easier to use Taguchi approach in application. The most common analysis technique by computer and all tables and plots in this research was processed using (MINITAB16).

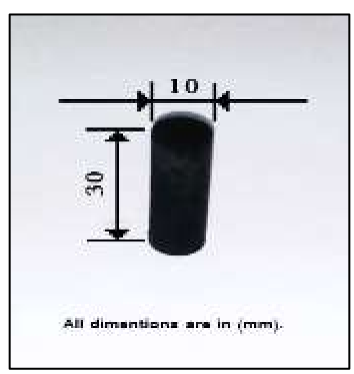
Experimental work:

Engineering products like: cams, gears, shafts, pinions, keys, hand tools, agricultural equipment... etc, are usually produced from a low carbon steel alloys. In this research experiments were done on low carbon steel specimens fabricated according to (ASTM- A276). The chemical composition of the steel is given in table (1).

Table (1): Spectrochemical analysis of steel (1020) ASTM (A276)

Element	Fe	C	Mn	P	S	Cr	Mo	Si
Wt%	Rem.	0.17	0.3	0.01	0.01	0.006	0.002	0.14

The prepared steel specimens were embedded in the carburizing box, which was filled with carburizing agent (Graphite) and then it was tightly sealed with clay cover to prevent unwanted furnace gas from entering the carburizing box during heating, this can be shown in figure (1).



(a) **(b)**

Figure (1): a: Carburizing box clay cover, b: Carburized specimens.

The furnace temperature was adjusted to the required temperature (870, 910 and 950 ^{o}C), the loaded steel carburizing box was charged into the furnace. When each of the furnace temperature reaches the required carburizing temperature, it was then soaked at the temperature for the required time (2, 3 and 4 hours).The specimen was held at the specified time, the steel carburizing box was removed from the furnace and the specimen was quenched in water.

The carburized test specimens were tempered at a temperature of (80, 100 and 120 ^{o}C), held for an hour and then quenched in water. Hardness of carburized steel was determined using (Knoop microhardness test). The same trial was repeated five times to reduce experimental errors, the average value was quoted as the final hardness.Taguchi technique was used to plan the design of experiments. The Taguchi method is a powerful tool for improving productivity during research and development, so high quality products in a low cost can be achieved while production in short time [10]thus the marriage ofexperiment design with optimization can control parameters to obtain best results which is achieved in the Taguchi method. Orthogonal array (AO) provides a set of well balanced (minimum experiments).

Taguchi's signal-to-noise ratio (S/N) is a log-function of desired output, serve as objective function for optimization, help in data analysis and prediction of optimum results.

Experiments of micro hardness were conducted based on the Taguchi method of three levels, each level with three factors. The values taken by a factor are termed to be levels. The factors to be studied and their levels chosen are detailed in table (2):

Table (2): Factors and their levels of carburization

Factor	Factor Code	Levels		
		1	2	3
Carburization temperature (^{o}C)	A	870	920	950
Carburization time (hrs)	B	2	3	4
Tempering temperature (^{o}C)	C	80	100	120

The (S/N) ratio for micro hardness is calculated using the higher-the betterrule as depicted in the following equation [11]:

$$S/N = -10\ log\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right] \quad (1)$$

Where:(n) is the number of the experiments in the orthogonal array and (y_i) is the (ith) value measured. The corresponding (OA) according to the number of factors and their levels that will be used in the experiment. Table (3) shows (L_9) orthogonal array from table (2).

Table (3): The (L_9) orthogonal array

Experiment No.	Process Parameter		
	Carburization Temperature (^{o}C)	Carburization Time (hrs)	Tempering Temperature (^{o}C)
1	870	2	80
2	870	3	100
3	870	4	120
4	910	2	80
5	910	3	100
6	910	4	120
7	950	2	80

8	950	3	100
9	950	4	120

In this research, a pin on disc wear tests were performed on carburized steel which has been selected as work piece material. All experiments were performed by using a pin on disc wear apparatus. This machine facilitates study of wear characteristics in sliding contact under desired conditions. Sliding occurs between the stationary pin on a rotating disc. Normal load, sliding distance and sliding speed can be varied to suit the test conditions. The pin specimen was tested in pin on disc apparatus. To perform the test specimen was clamped in jaw. Pin weight losses were measured using an electronic balance having an accuracy of (±0.001 mg). Dry sliding wear tests were carried out using pin-on disk type wear tester at constant parameters, where the tests were conducted at (10 min, 20 N, 250 rpm -sliding speed and 6 cm - sliding distance).

An (L_9) orthogonal array was chosen to determine the responses of hardness and wear rate of the specimens. The experiment consists of (9) tests, each raw in the (L_9) orthogonal array and the columns were assigned with parameters. The orthogonal array table in the Taguchi design method was applied to testing data as shown in table (3).

Results and Discussion:

1- Taguchi results:

The Taguchi method depending on the objective, proposed three different mean square deviations for the signal- noise (S/N) ratios, which are [10]:

- Nominal – the better.
- Larger – the better.
- Smaller – the better.

The three different signal-noises (S/N) ratios, corresponding to (n) experiments are presented below:

- For nominal – the better:

$$S/N = -10 \log \left[\frac{1}{n}\sum_{i=1}^{n}(y_i - m)^2\right] = -10 \log \left[(\bar{y} - m)^2 + S^2\right] \quad (2)$$

- For larger – the better:

$$S/N = -10 \log \left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right] \quad (3)$$

- For – smaller the better:

$$S/N = -10 \log \left(\overline{y^2}\right) \quad (4)$$

Where: (S) denotes the standard deviation, (y_i) the data obtained from experiments, (n) represents the number of experiments.

In this research, an orthogonal array (L_9) based on Taguchi method was applied to design of experiments. The experimental results and response (S/N) ratio are summarized in table (4):

Table (4): Orthogonal experimental results for micro hardness and wear rate

Exp. No.	A	B	C	Knoop hardness	(S/N)Ratio	Wearrate (g/cm)	(S/N) ratio
1	1	1	1	610	55.7066	0.0000047	106.595
2	1	2	2	601	55.5775	0.0000043	107.230
3	1	3	3	577	55.2235	0.0000004	127.250
4	2	1	1	580	55.2686	0.0000005	125.368
5	2	2	2	550	54.8073	0.0000005	126.214
6	2	3	3	511	54.1684	0.0000067	103.427
7	3	1	1	518	54.2866	0.0000006	124.945
8	3	2	2	605	55.6351	0.0000054	105.304

9	3	3	3	603	55.6063	0.0000070	102.926

Results of individual and composite desirability:

The objective of this study is to identify an optimal setting that minimizes the wear rate under wear conditions and maximize the micro hardness for the carburized steel. To resolve this type of multi-output parameter design problems, an objective function of (x), is defined as follows:

$$DF = \left(\prod_{i=1}^{n} d_i^{wi}\right)^{\frac{1}{\sum_{i=1}^{n} w_i}} \quad (5)$$

$$F(x) = -\ DF \quad (6)$$

Where: (d_i^{wi}) is the composite desirability defined for the (i^{th}) targeted output and the (w_i) is the weighting of the (d_i^{wi}). For various goals of each targeted output, the desirability (d_i^{wi}) is defined in different forms [8].

For the one-sided transformation:

$$d_i = \begin{Bmatrix} 0 \\ \left(\frac{\dot{y}_i - y_i^{(min)}}{y_i^{(max)} - y_i^{(min)}}\right)^r \\ 1 \end{Bmatrix} \quad if \quad \begin{matrix} \dot{y}_i \le y_i^{(min)} \\ y_i^{(min)} \le \dot{y}_i \le y_i^{(max)} \\ y_i^{(max)} \le \dot{y}_i \end{matrix} \quad (7)$$

The rate of increase for the desirability (d_i) in the (i^{th}) response depends on the variable (r) in the equation. For the three possible choices of (r) the following statements to hold, when the desirability is constant, the relationship between (y_i) and (d_i) is thought to be linear, and the value of (r) is taken as one. When ($\dot{y}_i$), above the minimum acceptable values ($y_i^{(min)}$) are of decreasing marginal worth, the relationship between (d_i) and ($\dot{y}_i$) is thought to be concave and the value of (r) is taken as less than one. When ($\dot{y}_i$) above the minimum acceptable values ($y_i^{(max)}$) are of increasing marginal worth, the relationship between ($\dot{y}_i$) and (d_i) is thought to be convex and the value of (r) is taken as greater than one [10].

For the two-sided transformation:

$$d_i = \left\{\left(\frac{\dot{y}_i - y_i^{(min)}}{T_i - y_i^{(min)}}\right)^s\right\} \quad , \text{if} \quad y_i^{(min)} \le \dot{y}_i \le T_i \quad (8)$$

$$d_i = \left\{\left(\frac{\dot{y}_i - y_i^{(min)}}{T_i - y_i^{(min)}}\right)^t\right\} \quad , \text{if} \quad T_i \le \dot{y}_i \le y_i^{(max)} \quad (9)$$

$$0 \quad \text{Otherwise}$$

As with (r), the value of (s) and (t) can be selected to reflect constant, increasing or decreasing incremental worth of ($\dot{y}_i$) as it approach (T_i).The individual desirability (weighted desirability-(d_i)) is calculated for all responses (micro hardness and wear rate) depending upon the type of quality characteristics, the selection of quality characteristic of micro hardness and wear rate are larger-the-better and smaller-the-better respectively [10]. The computed individual desirability for each quantity characteristics using equation (8) and (9) are shown in table (5):

Table (5): Individual of composite desirability

Normalized Values (micro hardness)	Normalized Values (wear Rate)	Weighted Desirability (micro hardness)	Weighted Desirability (wear Rate)	Composite Desirability	Rank
1	0	1	0	0	9
0.916064670	0.083935079	0.957112673	0.289715514	0.277290390	4
0.685939842	0.314059757	0.828214853	0.560410347	0.464140173	2
0.715223565	0.284776053	0.845708913	0.533644126	0.451307593	3
0.415319535	0.584679888	0.644452896	0.764643635	0.492776805	1
0	1	0	1	0	8
0.076829285	0.923169919	0.27718096	0.960817318	0.266320267	5
0.953523283	0.046476490	0.976485168	0.215584067	0.210514644	7
0.934825037	0.065174724	0.966863505	0.255293408	0.246833879	6

The composite desirability values are calculated using the equation [10]. Equal weightage is given to all responses (w_1=w_2= ½ and w=0.5). Finally these values are considered for optimizing the multi response parameter design problem. The results are given in the table (6):

Table (6): Optimizing the multi response parameter design problem.

Level		Carburization Temperature (^oC)	Carburization Time (hrs)	Tempering Temperature (^oC)
1		0.24714	0.23921	0.07017
2		0.31469	0.32686	0.32514
3		0.24122	0.23699	0.40775
Delta		0.07347	0.08987	0.33757
Rank		3	2	1

From the value of composite desirability in table (6), the parameter effect and the optimal level are estimated. The results are tabulated in table (6) and parameter effects are plotted in figure (2).

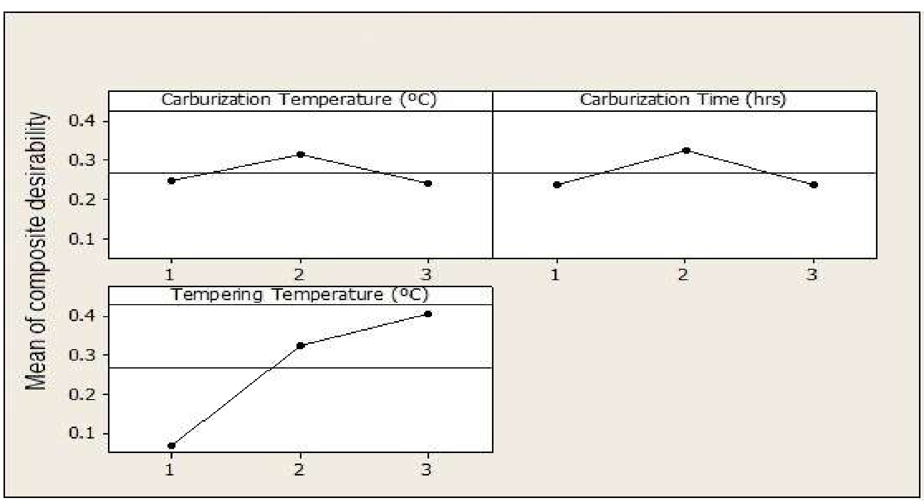


Figure (2): Mean plot of composite desirability.

Considering the maximization of composite desirability value in (table (6) and figure (2)), the optimal parameter condition is obtained as:

- Carburization temperature level (2).
- Carburization time level (2).
- Tempering temperature level (3).

Results of (ANOVA) for composite desirability:

The purpose of using (analysis of variance-ANOVA)is to investigate which carburization parameter significantly affect the performance characteristic [9]. This is accomplished by separating the total variability of the composite desirability, which is measured by the sum of the squared deviations from the total mean of the composite desirability, into contributions by each carburization parameter and the error. Thus:

$$SS_T = SS_F + SS_e \quad (10)$$

Where:

$$SS_F = \sum_{j=1}^{p} (\gamma_j - \gamma_m)^2 \quad (11)$$

Where:

SS_T:Total sum of squared deviations about the mean.
γ_j : Mean response for the (j^{th}) experiment.
γ_m : Ground mean of the response.
p : Number of experiments in the orthogonal array.
SS_F:Sum of squared deviations due to each factor.
SS_e: Sum of squared deviations due to error.

In addition, (F) test was used to determine which carburization parameters have a significant effect on the performance characteristic. ANOVA results for composite desirability are shown in table (7):

Table (7): ANOVA table for composite desirability

Source Variation	Degree of freedom (DF)	Sum of squares (SS_F)	Mean sum of squares (SS_e)	F-ratio	Contribution present
Carburization temperature (^oC)	2	0.0564	0.0282	0.593	7%
Carburization time (hrs)	2	0.0498	0.205	4.305	48%
Tempering Temperature (^oC)	2	0.2842	0.143	2.985	34%
Error	2	0.09523	0.048	-	11%
Total	8	0.48563	-	-	100%

From the ANOVA results, the carburization time and tempering time were found to have significant influence on the wear rate and micro hardness of carburized steel, compared to the influence of carburization temperature.

Mathematical model:
The relationship between the factors (carburization temperature, carburization time and tempering time) and the performance measures (composite desirability, micro hardness and wear rate) were modeled by multiple linear regression. The following equations are the final models in terms of encoded parameters:

Composite Desirability = - 0.0617486 - 0.0029603 * Carburizing Temperature (^oC)- 0.00110897 * Carburizing Time (hrs) +0.168787 * Tempering Temperature (^oC). (12)

Micro hardness (VHN) = 626.111 - 10.3333 * Carburizing Temperature (^oC) -2.83333 * Carburizing Time (hrs) - 13.5 * Tempering Temperature (^oC). (13)

Wear Rate (g/cm) = $4.42758*10^{-6}$ + $6.11983*10^{-7}$ * Carburizing Temperature (^oC)+$1.42152*10^{-6}$ * Carburizing Time (hrs) - $2.56018*10^{-6}$ *Tempering Temperature (^oC). (14)

From the equation (1), surface plot for composite desirability at different tempering temperature and carburization temperature are plotted as shown in figure (3). This surface plot can help in the prediction of the composite desirability at any zone of the experimental domain. It is clear from this plot that the composite desirability increases with increase in tempering temperature and carburization temperature.

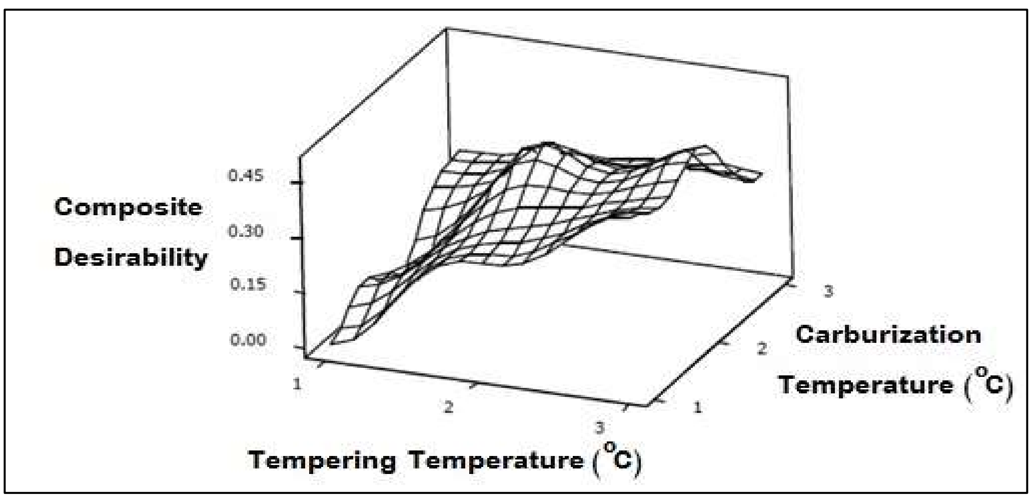


Figure (3): Relationship of composite desirability and carburization temperature, tempering temperature.

From equation (1), surface plot for composite desirability at different carburization time and carburization temperature are plotted as shown in figure (4). It is observed from this plot that composite desirability will improve at the middle values of carburization time and carburization temperature.

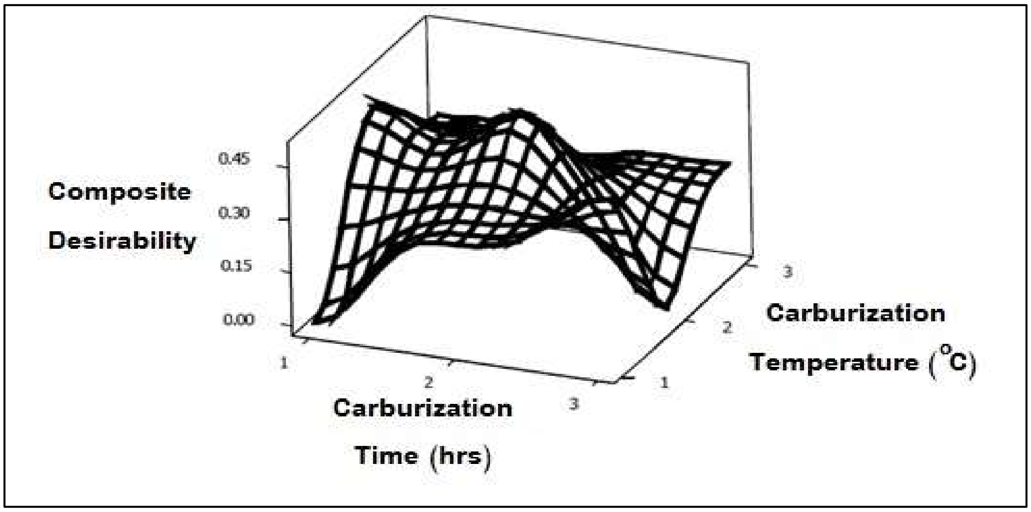


Figure (4): Relationship of composite desirability and carburization temperature, carburization time.

Finally, figure (5) is the representation of surface plot which shows the effect of both the carburization time and tempering temperature on the composite desirability.

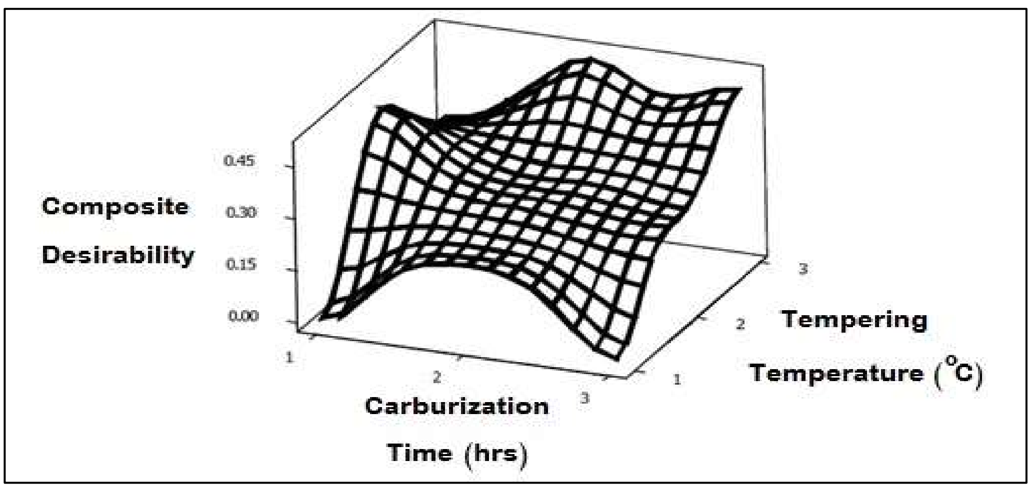


Figure (5): Relationship of composite desirability and tempering temperature, carburization time.

The surface plot for the figure (5) shows that the minimum value of composite desirability is obtained at the lower levels of both carburization time and tempering temperature.

Confirmation test:

Confirmation test is a final step recommended by Taguchi to verify experiment conclusion [8]. The improvements of the performance characteristics, using the optimal level of carburization parameters are verified. Estimated composite desirability [10] is calculated as follows:

$$\zeta_{opt} = \zeta_m + \sum_{i=1}^{q}(\zeta_i - \zeta_m) \tag{15}$$

Where:

ζ_m: is the total composite desirability.

ζ_i: mean composite desirability at optimum level.

(q): the number of process parameter having significant contribution in multiple performance characteristics.

As noted from table (4), the micro hardness is increased from (610 to 663) which were measured by(Knoop) method and the wear rate decreased from (0.0000047 to 0.0000029). The estimated composite desirability is increased from (0.2772 to 0.5138). It is clearly shown that the multiple objectives of the carburization process are together improved remarkably.

Table (5): Optimum process parameters results

	Initial process parameters	Prediction	Experiments
Level	A1 B1 C1	A2 B2 C3	A2 B2 C3
Micro hardness	610	-	663
Wear rate	0.0000047	-	0.0000029
Composite desirability	0.2772	0.5138	-
Improvement of composite desirability	-	0.2366	-

CONCLUSIONS:

For optimization of process which consists of less number of experiments mostly Taguchi method is used. Essential requirements of carburization process are higher hardness and lower wear rate. In this work, it was focused on using Taguchi method coupled with desirability function analysis for solving multi-criteria optimization problem in the field of carburization process. The following conclusions were obtained:

1- Experimental results showed that micro hardness and wear rate of carburized steel (1020) were greatly optimized by using desirability function analysis.

2- The optimal set of parameters obtained were carburization temperature (A2=920 ^{o}C), carburization time (B2= 3 hours) and tempering temperature (C3=120 ^{o}C).

3- The contribution of carburization time is maximum followed by tempering temperature and carburization temperature.

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