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Modeling of Cooling Rate in Water Quenched Process

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Author's contribution

The sole author designed, analyzed and interpreted and prepared the manuscript.

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ABSTRACT

Aim: The present study investigated the effect of operating parameters in modeling the cooling rate of water quenched process.
Methodology: A three factor, three levels Box-Behnken design (BBD) of RSM was applied to determine the effects of three independent variables (Time (A), radial distance (B) and immersion speed (C)) on cooling rate. Response surface analysis method was employed to optimize the parameters in the experiment.
Results: Data analysis shows that A, AB, BC, A^2 and B^2 are the terms which significantly affected the cooling rate at 95% confidence level. The experimental values were very close to the predicted values and were not statistically different at $p<0.05$. Optimum cooling rate of 4.75ºC/s was obtained when the time, radial distance and immersion speed were 2.50 minutes, 7.91 mm and 0.22 m/s respectively.
Conclusion: The regression model obtained has provided a basis for selecting optimum process parameters for the cooling rate during water quenching process.

Keywords: Quenchant; RSM (Response surface methodology); authenization; box behnken design.

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1. INTRODUCTION

The quenching process is a heat treatment widely used to improve the mechanical properties of steel products, such as hardness, stiffness, and strength, by the means of opportune solid-solid phase changes, induced by a heating, holding, and cooling thermal cycle [1]. The main purpose of the heating and the holding stages is the transformation of the starting material structure into a homogeneous austenitic phase, while, during the last stage of the process, forced cooling of the workpiece is used to induce the opportune decomposition of austenite into several microstructures, such as martensite, pearlite, bainite, ferrite, and Fe-carbide, depending on the chemical composition of the processing steel and the local cooling rate.

The timing of each step, as well as the heating and cooling rates and the holding temperature, are very important [1]. In recent years, a remarkable interest has been focused on the analysis and optimization of the quenching process, in order to obtain the desired phase changes, to reduce distortion and residual stress, to develop relatively shorter and less expensive thermal cycles. Computational analysis, based on the finite element, finite difference, or finite volume methods, is increasingly being used to effectively investigate and optimize complex manufacturing processes and thermal treatments, allowing the evaluation of properties not always experimentally measurable [2-5]. Woodard et al. [6] proposed a finite element two-dimensional procedure for the FEA of the quenching process of a 1080 cylinder, evidencing the relevance of the latent heat due to phase change. The same benchmark has been used for the validation of the models proposed by Huiping et al. [7] and by Kang et al. [8,9]. A FE model of the Jominy end-quench test for the evaluation of the transient temperature, including phase transformations, has been proposed and tested by Homberg [10]. However, the aforementioned works are restricted only to the cooling stage of the quenching process, assuming the initial structure as being totally austenitic. No consideration has been reported on the specific heating and holding cycle to be followed [1].

To obtain the desired microstructure transformation and good properties of the metal during quenching process, it is essential to have a complete control over the relevant process parameters to maximize the cooling rate on which the quality of a quenching is based. Therefore, it is very important to select and control the quenching process parameters for obtaining the maximum cooling rate. Various prediction methods can be applied to define the desired output variables through developing mathematical models to specify the relationship between the input parameters and output variables. The response surface methodology (RSM) is helpful in developing a suitable approximation for the true functional relationship between the independent variables and the response variable that may characterize the nature of the quenchant [11]. It has been proved by several researchers [12-15] that efficient use of statistical design of experimental techniques, allows development of an empirical methodology, to incorporate a scientific approach in the quenching processes. This paper deals with the modeling and the computational analysis of the transient temperature field of cooling rate and the microstructure transformations related to the quenching process of a eutectoid plain carbon steel using Response Surface Methodology in Design Expert 8.0.3 version.

2. METHODOLOGY

2.1 Sample Collection and Preparation

A solid cylindrical mild steel bar (AISI1020) purchased at local steel market in the form of 105 mm and 35 mm diameter rods was machined at the Fabrication workshop, Department of Mechanical Engineering, Faculty of Engineering and Technology, LAUTECH, Ogbomoso Nigeria to produce a specimen of 100 mm long of 30 mm diameter illustrated in Fig. 1. Three 2 mm diameter hole are drilled to a depth of 5 mm at 5 mm, 15 mm and 25 mm from outside diameter of the specimen, to accommodate the thermocouples that are used for temperature measurements. Ten samples of the specimen are produced and used for the experiment. The composition analysis of the as-received steel was carried out at Universal Steels Limited (Lagos, Nigeria) using spectrometer model 3460. Conventional water was used as quenchant for the steel. The compositional analysis of the metal sample is shown in Table 1.

2.2 Experimental Set-up

The prepared samples of steel probes of length 100 mm and diameter 30 mm were connected with a chrome/alumel K-type thermocouple via a tight fitting screw to prevent the quenching media from entering the drilled holes during quenching.

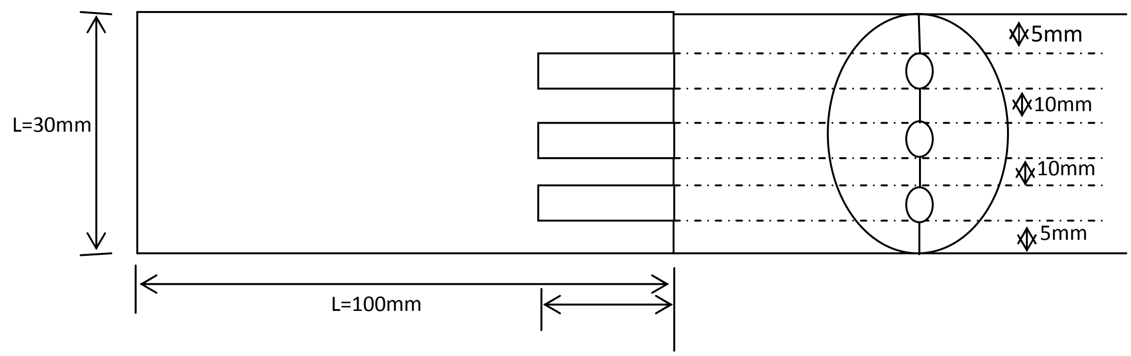


Fig. 1. Schematic diagram of the steel probe

Table 1. Composition analysis of the steel sample

C (%)	Si (%)	Mn (%)	S (%)	P (%)	Cr (%)	Ni (%)	Cu (%)
0.189	0.207	0.497	0.021	0.022	0.101	0.073	0.174
Nb (%)	**Al (%)**	**B (%)**	**W (%)**	**Mo (%)**	**V (%)**	**Ti (%)**	**Fe (%)**
0.0050	<0.0001	0.0011	<0.0001	0.0026	0.0018	0.0004	98.7

The thermocouples were connected to a 12 channel temperature recorder model BTM-4208 SD with SD data logger to conduct the data acquisition process of the temperature and time.

The complete assembly of the specimens (the specimen and thermocouples) was placed in a temperature controlled furnace Vaster 232 models available at the New Chemical Laboratory, Department of Chemical Engineering, LAUTECH, Ogbomoso Nigeria. Heated and soaked at an austenitized temperature of 850ºC for one hour to promote complete austenitization of the specimen. The heated specimen was quickly transferred from the furnace into 1000 ml quenching medium contained in a vertical tank under static condition and the probe dipped horizontally as practiced in industry via an immersion rig which consists of a one horse power electric motor and a voltage regulator. The speed of the electric motor which represents the speed of the immersion of the heated specimen was monitored with a digital tachometer model DT-2234B. The heating and quenching procedures were performed for immersion speed of 0.1 m/s, 0.35 m/s and 0.6 m/s using water as quenchants.

2.3 Development of Mathematical Model Using RSM

Response surface methodology (RSM) is a collection of mathematical and statistical technique useful for analyzing problems in which several independent variables influence a dependent variable or response and the goal is to optimize the response [14]. Inmany experimental conditions, it is possible to represent independent factors in quantitative form as given in Eq.(1).

Where Y is the response, f is the unknown function of response, X1, X2,…Xn are the input variables which can affect the response, n is the number of independent variables and is the statistical error that represents other sources of variability not accounted for [16]. In this study, Box–Behnken design with three factors and three levels was designed as shown in Table 2 and some mathematical models are used to regress the Box–Behnken design results by the mixed regression method and response surface method. These mathematical models show the dependency of cooling rate of quenched steel in water on the design variables which are time, radial distance and immersion speed.

Table 2. Experiment design for the three variables with three levels

Factors	Code	Level		
		Low (-1)	**Standard (0)**	**High (+1)**
Time (s)	A	2	51	100
Radial distance (mm)	B	5	15	25
Immersion speed (m/s)	C	0.1	0.35	0.6

The second order polynomial (regression) equation used to represent the response surface *Y* is given in equation 2 by [15].

Where Y is predicted response used as a dependent variable, represents the overall mean, represents the linear effect of the input factor x_i; represents the quadratic effect of the input factor x_i; represents the linear by linear interaction effect between the input factor x_i and x_j and ε is the random error term. The quality of fit of the polynomial model was expressed by the coefficient of determination (R^2), adjusted coefficient (R^2_{adj}) and predicted coefficient (R^2_{pred}).

3. RESULTS AND DISCUSSION

The adequacy of the developed model was tested using the analysis of variance (ANOVA) technique and the results of second order response surface model fitting in the form of analysis of variance (ANOVA) are given in Table 3. The determination coefficient (*R*2) indicates the goodness of fit for the model. The input parameter which is most significant on the output performance (cooling rate) is input parameter A which is Time because it shows the largest F-value of 1794.712 and minimum prob>F value, followed by the radial distance and the least effect is seen on immersion speed because of its least F-value of 1.394489. For two factors interaction, input combination of time and radial distance has the highest F-value of 10.87006 and thereby most significant on the output performance. Model F-value of 259.1327 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, AB, BC, A2, B2 are significant model terms. For two factors interaction, input combination of time and radial distance has the highest F-value of 10.87006 and thereby most significant on the output performance. The model fits was also checked by the correlation coefficients (R^2) = 0.9970, pred.R^2 = 0.9521 and adj.R^2 =0.9932 which revealed that the regression models are statistically reliable, dependable and significant. Adequate Precision measures the signal to noise ratio, a ratio greater than 4 is desirable. The adequate precision of the model was 43.3565; indicating an adequate and reliable regression model. Table 4 shows the experimental design of variables and the results in terms of actual values and predicted values. The residual values show little or no disparity between the predicted and experimental values of the cooling rate.

Also, the quadratic model equation for the cooling rate for the quenching process was given as follows;

$$Y= 5.01934 - 0.11079 (A) + 0.027721 (B) - 0.55059 (C) + 4.5306 \times 10^{-4} (A) (B) + 1.0306 \times 10^{-3} (A) (C) + 0.0801 (B) (C) + 6.1244 \times 10^{-4} (A^2) - 2.9247 \times 10^{-3} (B^2) -1.3256(C^2) \quad 3$$

The interactive effects of the input parameters on the cooling rate prediction were shown in Fig. 2(a-c). The response surface plots between time and radial distance for determining their effects on cooling rate at constant immersion speed 0.35m/s was show in the Fig. 2(a). At 2 seconds and radial distance 5mm, the cooling rate was found to be 4.65ºC/s and at 100 seconds and 5 mm, the cooling rate was 0.356ºC/s. Also at radial distance of 15mm and 51 seconds, cooling rate was found to be 1.15ºC/s. Thus, the cooling rate decreases at increased time and radial distance.

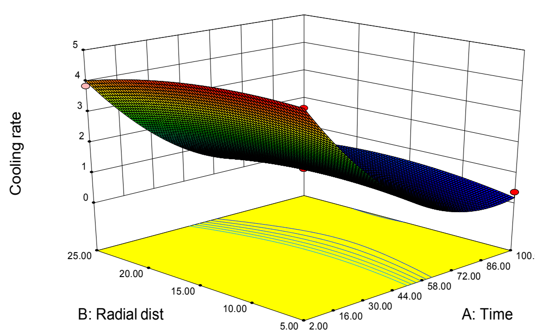
Fig. 2(b) shows the interaction plots for the effect of time and immersion speed on cooling rate at fixed Radial distance of 15 mm. The response surface plots indicated that an increase in time resulted in decrease in cooling rate with less effect by immersion speed. At immersion speed of 0.10 m/s and time 2 seconds, the cooling rate was found to be 4.713ºC/s and at high immersion speed value of 0.60 m/s and 2 seconds, the cooling rate was 4.575ºC/s. When time was increased to 100 seconds at immersion speed of 0.10 m/s, the cooling rate was found to be 0.475ºC/s.

The effect of radial distance and immersion speed on the cooling rate at fixed time of 51 seconds was showed in Fig. 2c. At low immersion speed of 0.10 m/s and radial distance 5 mm, the cooling rate was found to be 1.031ºC/s and at radial distance of 5 mm and 0.60 m/s immersion speed, the cooling rate was 0.518ºC/s. Also, at radial distance 25mm and 0.10 m/s, the cooling rate was 0.631ºC/s and at 25 mm and 0.60 m/s, cooling rate was found to be 0.9187ºC/s. This therefore indicated that as immersion speed increases over a low radial distance 5 mm, the cooling rate decreases and as immersion speed increases over a high radial distance 25 mm, cooling rate increases. Fig. 3

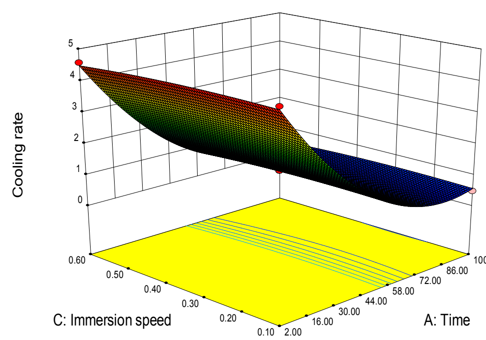
shows the plot of experimental data against the predicted data. The data were arranged along the straight line showing less disparity with R-value of 0.997.

Table 3. ANOVA of cooling rate response surface quadratic model for water

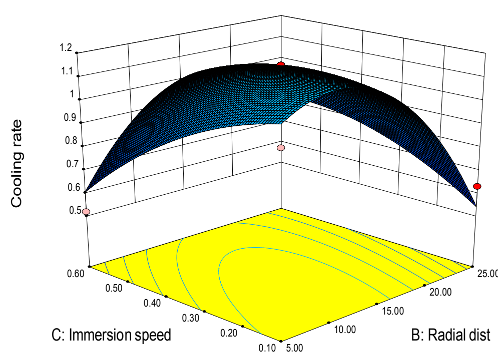
Source	Sum of squares	DF	Mean square	F value	p-value Prob > F	
Model	42.29593	9	4.6995	259.133	<0.0001	Significant
A	32.54833	1	32.5483	1794.712	<0.0001	
B	0.063243	1	0.0632	3.487	0.1041	
C	0.02529	1	0.0253	1.394	0.2762	
AB	0.197136	1	0.1971	10.870	0.0132	
AC	0.000638	1	0.0006	0.035	0.8566	
BC	0.16028	1	0.1603	8.838	0.0207	
A^2	9.104407	1	9.1044	502.016	<0.0001	
B^2	0.360175	1	0.3602	19.860	0.0029	
C^2	0.028902	1	0.0289	1.594	0.2472	
Residual	0.12695	7	0.0181			
Lack of fit	0.12695	3	0.0423			
Pure error	0	4	0			
Cor total	42.42288	16				



2b. 3D plot of immersion speed and time



2a. 3D plot of radial distance and time



2c. 3D plot of immersion speed and radial distance

Fig. 2. Response surface plots of input variables combination against the cooling rate

Table 4. Experimental result of water quenched steel

Run	Variables			Cooling rate		
	Time	Radial distance	Immersion speed	Actual	Predicted	Residual
1	2	15	0.6	4.58	4.49	0.09
2	2	25	0.35	3.86	4.03	-0.18
3	51	5	0.6	0.52	0.61	-0.09
4	100	15	0.6	0.39	0.48	-0.09
5	51	25	0.1	0.63	0.54	0.09
6	100	25	0.35	0.44	0.44	0.00
7	51	15	0.35	1.15	1.15	0.00
8	2	5	0.35	4.66	4.66	0.00
9	51	15	0.35	1.15	1.15	0.00
10	51	15	0.35	1.15	1.15	0.00
11	2	15	0.1	4.71	4.62	0.09
12	100	15	0.1	0.48	0.56	-0.09
13	51	25	0.6	0.92	0.83	0.09
14	51	5	0.1	1.03	1.12	-0.09
15	51	15	0.35	1.15	1.15	0.00
16	51	15	0.35	1.15	1.15	0.00
17	100	5	0.35	0.36	0.18	0.18

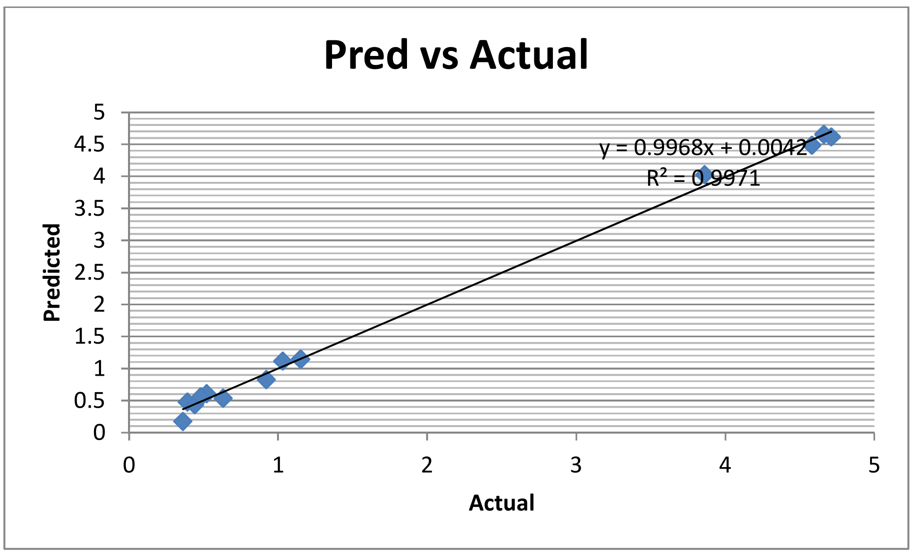


Fig. 3. Plot of predicted against actual values

4. CONCLUSION

This paper has described the use of design of experiments (DOE) for conducting experiments. A quadratic model was developed for predicting cooling rate of quenching process in water medium for a solid cylindrical mild steel bar (AISI1020) using response surface methodology. From this investigation, time had the greatest influence on cooling rate, followed by radial distance and the least effect was seen on immersion speed. A maximum cooling rate of 4.75ºC/s is exhibited by the water quenched process with the optimized parameters of 2.50 minutes time, 7.91 mm radial distance and 0.22 m/s immersion speed at desirability of 1.000. The model developed can be used for process behavior prediction for performance measure, for process optimization and for training tools for operators in industrial application.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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