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Optimization of Process Parameters for Temperature Distribution during Water Quenched Process

L. O. Mudashiru[1*], K. A. Adebiyi[1] and S. M. Adedayo[2]

[1]Department of Mechanical Engineering, Engineering Material and Occupational Safety Service, Ladoke Akintola University of Technology, Ogbomoso, Oyo State, Nigeria.
[2]Department of Mechanical Engineering, Production Engineering, University of Ilorin, Kwara State, Nigeria.

Authors' contributions

This work was carried out in collaboration between all authors. All authors read and approved the final manuscript.

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ABSTRACT

Wide application and versatility of steel have resulted in the need to improve its mechanical properties at desired temperature and microstructure to achieve production goal and reliable service performance. Quenching, a method of improving mechanical properties of steel, is characterized with reworking and induced thermal stresses leading to defective product. This could be caused by low temperature was distributed in the steel sample to effect the desired mechanical property. This paper is aimed at rectifying this anomaly by investigating the synergetic effect of operating variables (quenching time, radial distance and immersion speed) on temperature distribution in the quenched steel using Box-Behnken design of Response Surface Methodology (RSM). Results of the investigation show the significant terms to temperature distribution with

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**Corresponding author: E-mail: lomudashiru@lautech.edu.ng;*

quenching time having the most influential effect on the model development. The temperature distribution of 37.24°C was obtained at optimum condition for the parameters at 100 seconds, 15 mm radial distance and immersion speed of 0.10 m/s. The coefficient of correlation (R^2) obtained for water quenched gave 0.9999, Adjusted R^2 of 0.99983 and adequate precision of 43.356 respectively. This indicated a good agreement between the laboratory experiment and model developed for temperature distribution.

Keywords: Quenchant; box-behnkenn; analysis of variance (ANOVA); austenitization; Response Surface Methodology (RSM).

1. INTRODUCTION

Steels are the most common and widely used material in industries. They are relatively cheap, efficient, commercially available [1] and are the second largest produced material globally after cement, with about 1.3 million tons produced annually [2]. Steels are being used for manufacturing connecting and rotating components, rolling equipment, generator shafts and pressure vessels, due to their excellent mechanical properties such as high strength, high fatigue strength and elastic limit combined with reasonable ductility. An integral and important stage in heat treatment, is quenching which has an influence on microstructure changes and consequently on quality of final product [3].

Quench process involves raising the steel temperature above a certain critical value, holding it at that temperature for a specified time and then rapidly cooling it in a suitable medium to room temperature [4]. Mackerle [5] and Elmaryami and Omar [6] define quenching as a common manufacturing process, aiming to produce components with desirable properties such as low residual stresses and distortions, avoidance of cracks, specific hardness, and achievement of improved properties. It has also been described as one of the most common heat treatment processes used to impart the desire mechanical properties such as high strength, hardness and near resistance to metal parts using quenchants such as air, water and polymer solution [7,8]. Water, being the most readily available substance on Earth, has been used over time as quenching medium owing to its several advantages over other media such as its been inexpensive and non-toxic, no smoke or fume on quenching, easy to handle and poses no health or safety hazards and efficient in producing high strength steels with much lower alloying elements due to its great cooling speed [9].

The process of quenching introduces high temperature gradients within the material and this result in dimensional distortion, high level of residual stresses and low resistance to corrosion and surface cracking [8]. This defectposes challenges to the effectiveness of quenching and consequently account for rejected or reworked products, as well as additional overall manufacturing cost. Modeling of thermal distribution in quenching processes has become increasingly important to optimize process efficiency and produced reliable products with minimal cost as the variation of temperature distribution over time is of interest in many applications.

The response surface methodology was first developed by Box and Wilson [10] in the statistical field during the 1950s and is now broadly used in a lot of fields, such as chemical, agriculture, biological, and manufactures [11] and [12]. Elmaryami and Omar [6] investigated the effect of process history on metallurgical and material properties of an industrial quenched chromium steel bar AISI-SAE 8650 H. A mathematical model based on Finite Element Method was developed to predict temperature history and consequently the hardness of the quenched steel bar at any point to determine the Lowest Hardness Point (LHP). Gur and Tekkaya [13] developed a finite element model for predicting the temperature distribution field, volume fraction of phases and the evolution of internal stresses up to the residual stresses states during quenching of asymmetrical steel components. Huiping et al. [14] studied technological parameter optimization of gas quenching process using response surface methodology. This research is aimed at investigating the synergetic effect of operating variables on temperature distribution of quenched steel and optimization having water as the quenchant using Response Surface Methodology (RSM) in Design Expert software.

2. MATERIALS AND METHODS

2.1 Selection of Sample Material

AISI 1020 steel was selected for this work. The commercially available steel was purchased at local steel market in Nigeria in the form of 105 mm and 35 mm diameter rods. 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.

2.2 Experimental Set-up

The prepared samples of steel probes of length 100 mm and diameter 30mm as shown in Fig. 1 were connected with a chrome/alumel K-type thermocouple via a tight fitting screw to prevent the quenching medium from entering the drilled holes during quenching. 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. Heated and soaked at an austenitized temperature of 850°C 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 repeated twice for immersion speed of 0.1 m/s, 0.35 m/s and 0.6 m/s using water as quenchant.

2.3 Experimental Design

Response surface methodology has been used to study the optimization of chemical processes and products. Response surface methodology was used in this study to investigate the effect of some quenching parameters for the performance of the quenched steel in heat treatment process. A three factor, Box-Benken Design (BBD) model was used to design the experiment. Design-Expert version 8.0.3 was used for the modeling of the identified variables. The factors considered were quenching time, radial distance and immersion speed while the response is temperature distribution. The three variables at three different levels gave a total of seventeen (17) experimental runs shown in Table 1 in coded form where -1, 0,1 denoted minimum, midpoint and maximum values for each of the variables.

The quadratic response surface model considering all the linear terms, square terms and linear by linear interactions terms according to [15] was described as:

$$Y = \beta_o + \varepsilon \sum_{i=1}^{k} \beta_i x_i + \sum_{i-1}^{k} \beta_{ij} x_i x_j + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \varepsilon \qquad 1$$

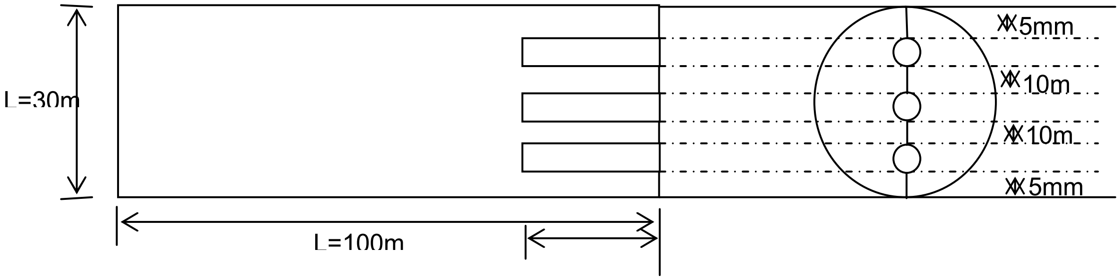


Fig. 1. Schematic diagram of the steel probe

Where Y is predicted response used as a dependent variable, β_o represents the overall mean, β_i represents the linear effect of the input factor x_i; β_{ij} represents the linear by linear interaction effect between the input factor x_i and x_j; β_{ii} represents the quadratic effect of the input factor x_i,k is the number of independent variables and ε is the random error term.

2.4 Statistical Data Analysis

Analysis of variance (ANOVA) was used for the analyses of the data obtained from experiment of the quenching medium. Theinteractions between the process variables and the responses of different regression models developed for temperature distribution using water as quenching medium was investigated. The quality of the fitted polynomial model was expressed by the coefficient of determination R^2, and its statistical significance was checked by the Fisher's F-test in the same in-built statistical program of the Design Expert 8.0.3. Model terms were evaluated by the P-value (probability) with 95% confidence level. Three dimensional surface plots and their respective contour plots were obtained for temperature distribution on the effects of the three factors (time, radial distance and immersion speed).

3. RESULTS AND DISCUSSION

3.1 RSM Analysis

The data were analyzed using multiple regression technique to develop a response surface model. The experimental design of variables and the results in terms of actual values and predicted values was shown in Table 2. A quadratic model was developed and tested for accuracies using the correlation coefficients (R-squared value). 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 (Temperature distribution) is input parameter (A) which is quenching time because it shows the largest F-value of 65194.770 and minimum prob>F value, followed by the immersion speed and the least effect is seen on radial distance because of its least F-value of 13.551. For two factors interaction, there is no significant effect on the output performance at 95% confidence level ($p<0.05$). The Model F-value of 10619.60 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, B, C and $A^2$are significant model terms. The accuracy of the predictions from the model equations was analyzed using R^2, Adjusted R^2 and Adequate precision. The water quenched process model prediction gave R^2 of 0.999927, Adjusted R^2 of 0.99983 and; and adequate precision of 43.356. The reported values show a 99.9% reliability of the empirical model developed for water quenched system.

The empirical model obtained for the temperature distribution for water quenching (Y) was given in equation 2 as:

$$\begin{aligned} &Temperature\ Distribution = \\ &\quad 889.63084 - 23.99858 * A - 0.75814 * B - 24.53082 * C + 2.19388e^{-003} * A * B + 0.32041 * A \\ &\quad * C + 0.5000 * B * C + 0.15458 * A^2 + 0.034750 * B^2 + 41.200 \\ &\quad * C^2 \end{aligned} \tag{2}$$

Table 1. Design of factors for temperature distribution

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

Table 2. Experimental result of water quenched steel

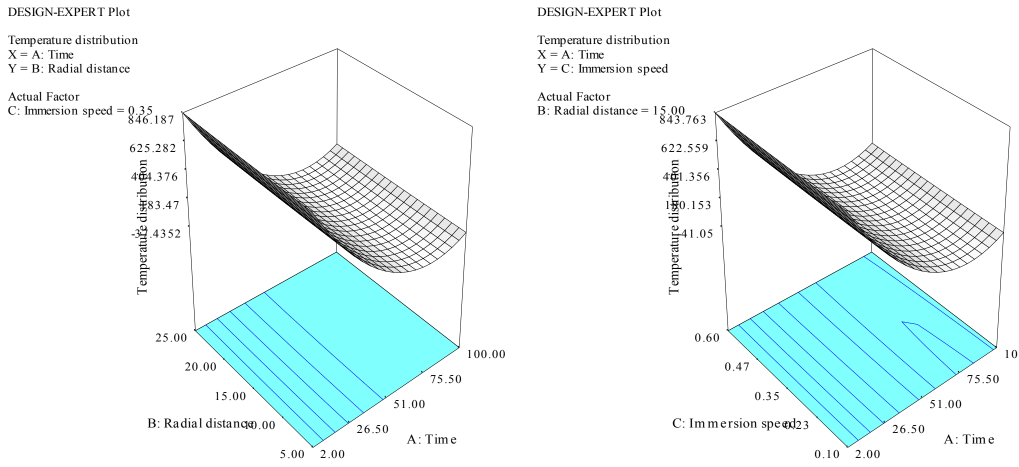
Run	Time A (s)	Radial distance B (mm)	Immersion speed C(m/s)	Temperature(°C) actual	Predicted
1	2	15	0.60	841.00	843.76
2	2	25	0.35	843.20	846.19
3	51	5	0.60	76.10	76.83
4	100	15	0.60	56.90	59.16
5	51	25	0.10	74.90	74.18
6	100	25	0.35	52.40	55.89
7	51	15	0.35	70.70	70.70
8	2	5	0.35	840.40	836.91
9	51	15	0.35	70.70	70.70
10	51	15	0.35	70.70	70.70
11	2	15	0.10	839.80	837.54
12	100	15	0.10	40.00	37.24
13	51	25	0.60	96.50	90.75
14	51	5	0.10	59.50	65.25
15	51	15	0.35	70.70	70.70
16	51	15	0.35	70.70	70.70
17	100	5	0.35	45.30	42.31

Table 3. ANOVA of temperature response surface quadratic model for water quenching

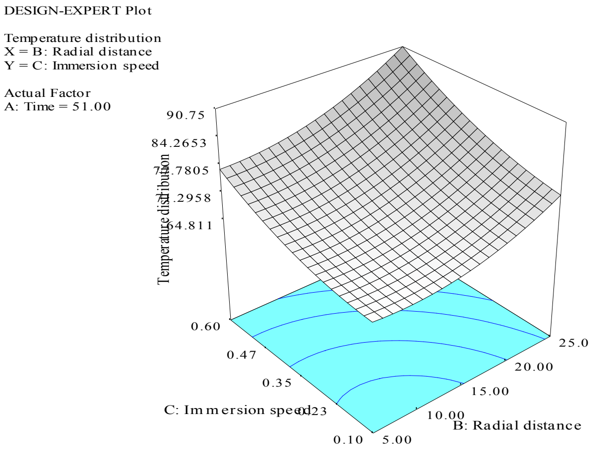
Source	Sum of Squares	df	Mean Square	F Value	P-value Prob>F	
Model	1841245	9	204582.833	10619.600	<0.0001	significant
A	1255954	1	1255954.005	65194.770	<0.0001	
B	261.0613	1	261.061	13.551	0.0078	
C	396.2112	1	396.211	20.567	0.0027	
AB	4.6225	1	4.623	0.240	0.6392	
AC	61.6225	1	61.622	3.199	0.1168	
BC	6.25	1	6.250	0.324	0.5868	
A^2	580009.8	1	580009.779	30107.480	<0.0001	
B^2	50.84474	1	50.845	2.639	0.1483	
C^2	27.91842	1	27.918	1.449	0.2678	
Residual	134.8525	7	19.265			
Lack of fit	134.8525	3	44.951			
Pure error	0	4	0			
Cor total	1841380	16				
Std. dev.	4.389		R-squared	0.9999		
Mean	248.206		Adj R-squared	0.9998		
C.V. %	1.768		Pred R-squared	0.9988		
PRESS	2157.640		Adeq precision	240.307		

3.2 Synergetic Effect of the Factors on Performance of Temperature Distribution during Quenching Process using Water as Quenchant

Figs. 2a,b and c show the 3D surface interaction plots for determining the effects of the operating parameters on temperature distribution. In Fig. 2a), effect of time and radial distance against the temperature response at constant immersion speed of 0.35 m/s was shown. At radial distance of 5 mm and time 2 seconds, the temperature was found to be 840.4°C and at radial distance of 25 mm and 2 seconds, the temperature value was 843.2°C. This therefore indicated that decreased temperature value was enhanced by increased time with less effect by radial distance.



2a). 3D plot of Radial distance and time **2b). 3D plot of immersion speed and time**



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

Fig. 2. Response surface plot of input parameters against the temperature distribution

The responses observed for the effects of time and immersion speed on temperature at fixed radial distance 15 mm was shown in Fig. 2b). At low immersion speed 0.10 m/s and 2 seconds, temperature was shown to be 839.8°C and also, at immersion speed of 0.35 m/s and 51 seconds, the temperature was found to be 70.7°C. This indicated that temperature distribution of the quenched steel decreases as time and immersion speed increased.

Fig. 2c shows theeffects of radial distance and immersion speed on temperature at constant time of 51 seconds. This response plots indicated that high temperature was enhanced by increase in immersion speed and radial distance. At low immersion speed (0.10 m/s) and radial distance 5 mm, temperature was found to be 59.5°C. And at immersion speed of 0.60 m/s and radial distance 25 mm, temperature was observed to be 96.5°C. Therefore, temperature distribution of the quenched steel increases as immersion speed and radial distance increased. The experimental values of temperature distribution in the quenched steel sample was plotted against the predicted values as shown in Fig. 3. Less disparity was observed as the values fitted into each other with a correlation coefficient of 0.9999.

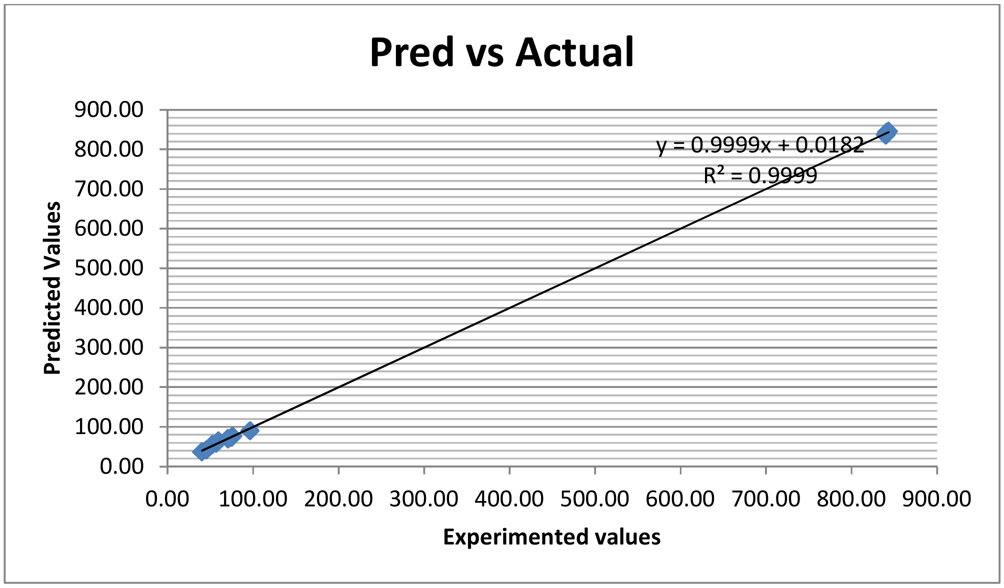


Fig. 3. Plot of predicted against actual values

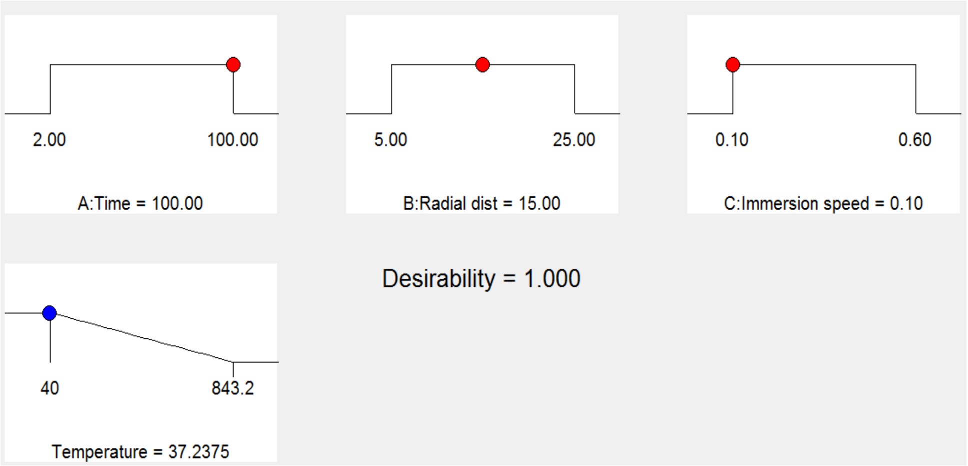


Fig. 4. Ramps to show optimization of process parameters on temperature distribution

3.3 Numerical Optimization of Process Parameters on Temperature Distribution for Water Quenched Steel

Numerical optimization was performed on the temperature distribution to get optimum value and optimum operating conditions. The input parameters time, radial distance and temperature were kept in range of 2-100 seconds, 5-15 mm and 0.10-0.60 m/s respectively. The temperature distribution was aimed at minimizing. Therefore, the temperature distribution of 37.24°C as shown in Fig. 4 (above) was obtained at optimum condition for the paramters at 100seconds, radial distance off 15 mm and immersion speed of 0.10 m/s. This was satisfactory since the desirability obtained was 1.000.

4. CONCLUSION

In this study, experiments has been carried out to obtain temperature-time history data at different immersion speed of 0.1 m/s, 0.35 m/s and 0.6 m/s, at different radial distances (5 mm, 15 mm, 25 mm) within the specimen. It was found that temperature drops rapidly in the early cooling period and as the cooling period progressed, the reduction in temperature attained an almost steady state with increasing cooling rate. The accomplished model equations gotten from response surface methodology were tested and found fully adequate. The coefficient of correlation (R^2) for water quenched prediction gave 0.999927, Adjusted R^2 of 0.99983 and adequate precision of 43.356 respectively. The reported values show a 99.9% reliability of the empirical models. From the investigation, it was found that time has greater influence on temperature distribution in the water medium, followed by radial distance and immersion speed.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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