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(RESEARCH ARTICLE)

Simulation modeling and optimization of bitumen –palm kernel oil blend for austempering of cast iron and steel

OC Okwonna *

Department of Mechanical Engineering, Michael Okpara University of Agriculture Umudike, Nigeria.

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Abstract

The study combines both simulation modeling and optimization of bitumen-palm kernel oil blend for austempering of cast iron and steel. Two independent factors namely austenitizing temperature (A) and holding time (H) were evaluated while five responses which includes ultimate tensile strength (u.t.s), hardness (h), impact strength (i), percentage elongation (e), percentage reduction in area (r.i.a) were evaluated. 3-D response surface and 2-D contour plots through response surface methods were used to estimate multi-response mathematical models. Desirability function approach provided by MINITAB 18 was used to determine the optimal settings of the response and factors after adequacy of the models to approximate the measured data had been established at 0.10 confidence level. From the result, optimum conditions for austenitizing temperature was 916.50C and 5 min while the predicted values of quenching hardness, ultimate tensile strength, impact strength, %elongation, %reduction in area were 1327.29MPa, 29.36J, 72.77%, 86.79% and 175.59HRC for 0.56%C-Steel; 1407.97MPa, 20.04J, 50.80%, 49.17% and 196.13 for 0.76%C-Steel; 1235.01MPa, 32.42J, 60.39%, 55.99% and 234.99HRC for ductile cast iron. Great improvement was seen in the steel performance after austempering process which gave rise to the conclusion that as the austempering time and holding time increases, that the mechanical properties of the steel were affected. Quenching of 0.56%C, 0.76%C-steel and ductile cast iron at the optimal settings using B-PKO saved one thousand naira (₦1000.00) showing 28.57% profit. The developed empirical models are recommended in some of the automobile and engineering industries during heat treatment operations so as to save time and energy.

Keywords: Optimization; Simulation modeling; Austenitizing temperature; Holding time; Austempered steel; Austempered cast iron

1. Introduction

Steel that are heat treated are of great importance in engineering and automobile industries for making elements such as gears, shafts, connecting rods, wheel spokes, and spanners because they are bound to have high strength, toughness and considerable hardness after quenching [1]. They can equally be used for production of springs (coiled and laminated), hammers, wood saws; used for making cutting tools such as drills, chisels, shear blades, knives due to their high wear resistance. Cast iron that are austempered can equally be utilized for making machine parts like connecting rods, brake drums, flywheels, crankshafts, dies, agricultural components, mining mechanism, transportation equipment, and rail parts [1].

Heat treatment is an industrial manufacturing process which is ultimately used to improve the mechanical properties of engineering alloy/materials. Among various forms of heat treatment processes which have been effectively used to enhance the mechanical properties includes annealing, normalizing, martempering, austempering and stress relieving and so on. Austempering is one the various forms of heat treatment methods utilized for hardening of ferrous

* Corresponding author: OC Okwonna
Department of Mechanical Engineering, Michael Okpara University of Agriculture Umudike, Nigeria.

metals/steels [2]. It involves heating to austenitizing temperature, quenching to a known temperature followed by soaking for a given time for sufficient phase transformation to take place and cooling to room temperature. Quenching includes the fast cooling of steel or cast iron in quenching media to acquire certain property. Quenching is utilized to improve the properties of steel by first introducing martensite when the steel is rapidly cooled through its eutectoid point and making the austenite unstable [1].

Austempering of steel and cast iron with bitumen-palm kernel oil blend and selected Nigeria vegetable oils were shown in the works of [3, 4, 5, and 6] but none established specific mathematical equations for developing the engineering products from it. Therefore, developing a mathematical design for austempering process of steel and cast iron from blend of bitumen-palm kernel oil in line with GISMA and BS EN ISO 9223 standard specifications will be of great importance in reechoing investors' interest in using locally sourced materials during heat treatment of steel and cast iron. Determination of the optimal performance of the quenchants used in austempering process is very important because it makes its use economical with regards to energy requirement and time spent during heat treatment operation thereby reducing much more production cost. These optimal conditions are realizable through application of response surface methodology. RSM in research studies is a very good tool for experimental results prediction and optimization of production conditions [7]. This therefore eliminates difficulties involved in experimental process, reduces more errors in experimental works and facilitates faster time duration involved during research findings. Hence, this work applied desirability function in response surface to develop a mathematical/simulation model for austempering process of steel and cast from bitumen-palm kernel oil blend in accordance with engineers and foundry people' desire.

2. Material and methods

This study involves experimental determination of the limits at which austenitizing temperature and holding time (factors) influence mechanical properties (responses) of steel and cast iron austempered from the blend of palm kernel oil-bitumen. The bitumen and palm kernel oil used was obtained directly from the local market and natural deposit. The mechanical properties evaluated include ultimate tensile strength (u.t.s), hardness (h), impact strength (i), percentage elongation (e), percentage reduction in area (r.i.a). The results of this test were used for investigating the concurrent impacts of main effects/interactions of the factors on the responses using the central composite design which was employed in this study to predict response surface models with quadratic effects and two factor interactions. The quadratic mathematical model to be developed takes this form:

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i i^2 + \sum_{i<j}^{\frac{k(k-1)}{2}} \beta_{ij} x_i x_j + \epsilon \qquad (1)$$

The obtained data were analyzed with iterative fitting/selection of best mathematical functions relating each of the responses and the factors using residual plots aided backward elimination method. The developed models were simulated with respect to austenitizing temperature and holding time prediction using Minitab response optimizer with desired setting of the mechanical properties of austempered steel and austempered ductile cast iron as target. The prediction accuracy of the simulation was confirmed experimentally with GISMA and BS EN ISO 9223 standard specifications for engineering components/automobile parts as set targets. The standard limits for tensile strength is ≥1100Mpa, for impact strength is >20J, for hardness test is >150HRv and poision's ratio is ≥0.3 and <1 for grade 1 steel then for grade 2 steel, the standard limit for tensile strength is ≥1150Mpa,for impact strength is >20J,for hardness test is >170HRv, for poision's ratio is ≥0.3 and <1 and ductile cast iron the standard limit for tensile strength is ≥1000Mpa, for impact strength is >20J, for hardness test is >150HRv, for poision's ratio is ≥0.3 and <1.

The steel and ductile cast iron were machined according to [8, 9, and 10] standards with lathe, hacksaw and milling machines and the machining operations were carried out at metallurgical training institute Obosi, Anambra State. The response samples each were prepared for a test and the specifications: 10 × 10 × 55 mm with a 2.5 mm notch (for impact test), 25 × 30 mm (for hardness test) as in figure 3.4c and 70 × 10 mm (for tensile strength). The blend of the bitumen-palm kernel oil boiled at 420^{0}C which was used as the austempering temperature during the experiment and the ratio for the mixture of the blend was 15:85 adopted from the work of [1]. Twenty samples from each of the alloys were all heated treated. The first five samples were given austenitizing heat treatment at 800^{0}C, soaked for 30 minutes at that same temperature then quenched in bitumen-palm kernel oil medium austempered at 420^{0}C for varying time intervals of 5 minutes, 15minutes, 30 minutes, 45 minutes and 60 minutes. Another second group of five samples were given austenitizing heat treatment at 840^{0}C, soaked for 30 minutes at that same temperature and then quenched in bitumen-palm kernel oil medium austempered at 420^{0}C for varying time intervals of 5 minutes, 15 minutes, 30minutes, 45 minutes and 60 minutes. The third groups of five samples were given austenitizing heat treatment at 900^{0}C and underwent the same processes as in the previous cases while the last group of five samples passed through the same austenitizing heat treatment at 960^{0}C.

The properties of the responses (U.T.S, %E, %R.I.A) were all determined in accordance with [1] research work, [11] and from the equation:.

$$U.T.S. = \frac{maximum\ load}{original\ cross{-}\sec - sectional\ area}$$

$$= \frac{maximum\ load}{Area\ of\ Original\ Cross{-}section}$$

$$= \frac{P_{max}}{A_O} \qquad (2)$$

Percentage Elongation in Area

$$\%E = \frac{Change\ in\ Length}{Ooriginal\ Length} \times 100\%$$

$$= \frac{L_1 - L_0}{L_0} \times 100\% \qquad (3)$$

Percentage Reduction in Area

$$\%\ R.I.A. = \frac{Change\ in\ Area}{Original\ Area} \times 100\%$$

$$= \frac{A_0 - A_1}{A_0} \times 100 \qquad (4)$$

Hardness test was determined using the equation

$$V.H.N. = \frac{2P}{\pi D\ [D - \sqrt{D2 - d2}]} \qquad (5)$$

Impact test determined using equation

Impact toughness

$$= \frac{Energy(J)}{Volume}$$

$$= \frac{energy}{\pi r 2h} \qquad (6)$$

Plastic pipe pattern of 30 mm by 200 mm length was in use during the preparation of sand mould made of silica that was used for the production of the cast iron. The moulding sand used was prepared by the addition of 13% bentonite which serves as the binder and 10 % water into silica sand according to [1] and [12]. The mould was prepared with cope and drag by pounding the prepared sand round the pattern so as to create cavity where the metal melted was poured with the next step was withdrawal of pattern from the mould. The charge preparation and the formulas for theoretical charge preparations were obtained from the work of [1].

The ANOVA of the experiment was conducted using MINITAB application. The define custom which is a tool seen in response surface was used to generate design from the data collected which will appear in the worksheet. The backward elimination method was used to develop the model. Using α = 0.10 rather than the commonly used α = 0.05 which help to enhance the power of the tests thereby increases the likelihood that important terms remain in the model. The residual of the mathematical models was analyzed graphically, and statistical significance of each of the terms in the models was also tested at 95% significance test approach, then the insignificant terms were expunged from the equations. Thereafter the reduced models were tested in line with the same experimental procedure described above to confirm the adequacy for the austempered steel and cast iron being studied. When the models have been fully validated, DFA was applied to confirm the optimal settings of the results that were tested experimentally to check the success of the prediction.

3. Results and discussion

The experimental results from the austenitizing temperature and holding time limits and multifactor-response evaluation of austempered steel and austempered ductile cast iron with blend of bitumen-palm kernel oil are as in Table 1 and 2 respectively while equations (7) to (21) constitute functions derived for predicting U.T.S, hardness test, Impact test, %E and %R.I. A of the austempered steel and cast iron.

Table 1 Limits of Materials for austempering of steel and ductile cast iron

S/No	Factor Description	Austenitizing temperature (High)	Low	Holding time (High)	Low
1	U.T. S	960	800	60	5
2	Hardness test	960	800	60	5
3	Impact tset	960	800	60	5
4	%E	960	800	60	5
5	%R.I. A	960	800	60	5

Table 2 Multifactor-response analysis of austempered steel and austempered ductile cast iron

Material	Time	Temperature	IMPACT Energy	TENSILE STRENGTH	HARDNESS	%R.I.A	%ELONGATION
0.76C	5	800	25.03	1056.80	201.01	44.01	44.77
0.76C	15	800	26.63	1061.27	149.21	44.11	45.13
0.76C	30	800	28.72	1078.71	140.22	44.15	44.24
0.76C	45	800	25.54	1083.20	140.52	43.06	43.65
0.76C	60	800	27.40	1072.60	140.38	44.14	43.71
0.76C	5	840	17.16	1130.79	206.18	47.98	47.21
0.76C	15	840	23.99	1135.16	175.16	48.05	47.36
0.76C	30	840	26.42	1152.74	155.35	48.11	45.94
0.76C	45	840	34.48	1163.16	171.97	49.12	44.77
0.76C	60	840	31.92	1169.98	165.29	48.03	44.92
0.76C	5	900	14.16	1265.58	210.00	56.11	47.23
0.76C	15	900	19.17	1270.98	195.23	56.58	48.54
0.76C	30	900	22.15	1290.96	178.16	56.61	47.77
0.76C	45	900	27.45	1310.79	183.06	55.02	47.21
0.76C	60	900	25.54	1320.07	175.06	56.62	48.54
0.76C	5	960	12.06	1407.20	260.51	58.82	48.57
0.76C	15	960	12.99	1416.16	238.12	59.02	49.28
0.76C	30	960	14.85	1423.35	217.33	59.16	50.78
0.76C	45	960	18.07	1428.16	197.05	58.91	48.57
0.76C	60	960	15.63	1431.79	187.01	59.13	48.95
0.56C	5	800	32.11	946.10	170.11	40.11	42.10
0.56C	15	800	32.82	900.12	155.71	30.21	33.21

0.56C	30	800	34.32	863.51	151.56	26.55	29.50
0.56C	45	800	32.95	894.65	153.71	33.62	35.60
0.56C	60	800	34.89	901.60	146.35	36.41	38.63
0.56C	5	840	23.98	1158.50	190.51	55.50	55.51
0.56C	15	840	39.62	1113.36	178.73	45.32	46.36
0.56C	30	840	42.39	1086.91	170.63	41.16	41.91
0.56C	45	840	40.36	1116.51	170.41	48.23	47.51
0.56C	60	840	37.27	1122.28	169.56	51.26	52.20
0.56C	5	900	21.13	1362.20	212.65	70.32	71.13
0.56C	15	900	24.21	1265.06	201.81	60.21	75.11
0.56C	30	900	20.38	1288.69	180.43	56.16	78.03
0.56C	45	900	31.96	1245.15	170.99	63.15	83.25
0.56C	60	900	35.23	1256.45	168.63	66.45	88.31
0.56C	5	960	16.18	1417.11	205.16	83.15	81.15
0.56C	15	960	17.21	1340.30	189.36	74.27	92.37
0.56C	30	960	20.12	1301.73	183.57	69.24	95.21
0.56C	45	960	14.41	1344.61	178.61	77.47	97.11
0.56C	60	960	21.23	1351.63	172.09	78.23	96.25
DI	5	800	39.71	936.65	210.01	47.18	47.21
DI	15	800	40.41	956.21	196.11	48.06	48.32
DI	30	800	41.91	976.13	195.96	48.11	49.17
DI	45	800	41.47	980.16	194.73	48.86	44.77
DI	60	800	41.04	988.79	193.67	49.16	45.16
DI	5	840	31.07	1014.93	229.98	53.48	53.74
DI	15	840	37.08	1021.16	227.16	53.65	52.75
DI	30	840	39.48	1027.73	225.12	54.36	52.15
DI	45	840	40.20	1031.18	223.26	52.98	52.54
DI	60	840	44.01	1045.25	221.92	54.48	52.61
DI	5	900	27.54	1120.16	233.94	56.11	53.72
DI	15	900	32.20	1143.27	232.95	56.58	55.78
DI	30	900	36.62	1160.21	230.74	56.61	55.68
DI	45	900	36.87	1165.16	230.71	57.63	53.70
DI	60	900	38.03	1180.08	229.62	56.62	53.75
DI	5	960	23.53	1215.16	240.61	60.82	56.41
DI	15	960	24.38	1239.85	238.43	61.02	56.82
DI	30	960	27.62	1240.88	236.21	61.16	56.96
DI	45	960	31.95	1265.16	235.91	61.67	56.41
DI	60	960	28.78	1270.47	235.88	61.27	56.96

Analysis of residuals associated with developed functions (Table 3-5) indicated their aptness for further analysis since constant variance assumption is not violated, hence, their simulation using response optimizer for predicting optimal levels of mechanical properties that will jointly satisfy the austempered steel and austempered ductile cast iron responses.

Table 3 Residual analysis of the developed prediction models for 0.56%C-Steel

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**		**P-Value**
Model	5	5589.9	1117.99	42.78		0.000
Linear	2	4519.4	2259.71	86.47		0.000
Time	1	2137.6	2137.61	81.79		0.000
Temperature	1	2353.9	2353.87	90.07		0.000
Square	2	1011.4	505.71	19.35		0.000
Time*Time	1	233.0	233.00	8.92		0.010
Temperature*Temperature	1	778.4	778.43	29.79		0.000
2-Way Interaction	1	112.6	112.57	4.31		0.057
Time*Temperature	1	112.6	112.57	4.31		0.057
Error	14	365.9	26.13			
Total	19	5955.8				
Model	3	1120.7	373.56	16.77		0.000
Linear	2	1003.4	501.71	22.52		0.000
Time	1	136.8	136.77	6.14		0.025
Temperature	1	866.7	866.65	38.90		0.000
Square	1	100.5	100.50	4.51		0.050
Temperature*Temperature	1	100.5	100.50	4.51		0.050
Error	16	356.5	22.28			
Total	19	1477.2				
Model	4	614984	153746	272.08		0.000
Linear	2	562704	281352	497.89		0.000
Time	1	5457	5457	9.66		0.007
Temperature	1	557247	557247	986.13		0.000
Square	2	60827	30414	53.82		0.000
Time*Time	1	9321	9321	16.49		0.001
Temperature*Temperature	1	51506	51506	91.15		0.000
Error	15	8476	565			
Total	19	623460				
Model	4	5546.69	1386.67	178.86		0.000
Linear	2	5169.50	2584.75	333.39		0.000
Time	1	2.95	2.95	0.38		0.547
Temperature	1	5166.55	5166.55	666.39		0.000

Square	2	401.64	200.82	25.90		0.000
Time*Time	1	345.38	345.38	44.55		0.000
Temperature*Temperature	1	56.26	56.26	7.26		0.017
Error	15	116.30	7.75			
Total	19	5662.99				
Model	3	10325.8	3441.9	97.18		0.000
Linear	2	10319.6	5159.8	145.68		0.000
Time	1	141.8	141.8	4.00		0.063
Temperature	1	10192.3	10192.3	287.76		0.000
2-Way Interaction	1	120.7	120.7	3.41		0.083
Time*Temperature	1	120.7	120.7	3.41		0.083
Error	16	566.7	35.4			
Total	19	10892.5				

Table 4 Residual analysis of the developed prediction models for 0.76%C-Steel

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Model	2	363861	181930	2613.76	0.000
Linear	2	363861	181930	2613.76	0.000
Time	1	3406	3406	48.93	0.000
Temperature	1	360455	360455	5178.58	0.000
Error	17	1183	70		
Total	19	365044			
Model	3	17973	5991.0	45.43	0.000
Linear	2	16533	8266.3	62.68	0.000
Time	1	5403	5403.3	40.97	0.000
Temperature	1	11129	11129.3	84.39	0.000
Square	1	1359	1359.5	10.31	0.005
Time*Time	1	1359	1359.5	10.31	0.005
Error	16	2110	131.9		
Total	19	20083			
Model	3	723.756	241.252	341.29	0.000
Linear	2	710.421	355.210	502.51	0.000
Time	1	0.001	0.001	0.00	0.967
Temperature	1	710.420	710.420	1005.01	0.000
Square	1	19.134	19.134	27.07	0.000
Temperature*Temperature	1	19.134	19.134	27.07	0.000
Error	16	11.310	0.707		

Model	3	723.756	241.252	341.29	0.000
Linear	2	710.421	355.210	502.51	0.000
Time	1	0.001	0.001	0.00	0.967
Temperature	1	710.420	710.420	1005.01	0.000
Square	1	19.134	19.134	27.07	0.000
Temperature*Temperature	1	19.134	19.134	27.07	0.000
Error	16	11.310	0.707		
Model	3	72.475	24.1583	40.69	0.000
Linear	2	71.634	35.8168	60.33	0.000
Time	1	2.108	2.1080	3.55	0.078
Temperature	1	69.373	69.3730	116.85	0.000
2-Way Interaction	1	2.006	2.0060	3.38	0.085
Time*Temperature	1	2.006	2.0060	3.38	0.085
Error	16	9.499	0.5937		
Model	4	693.71	173.428	21.80	0.000
Linear	2	617.43	308.715	38.81	0.000
Time	1	179.45	179.453	22.56	0.000
Temperature	1	437.98	437.977	55.06	0.000
Square	2	66.86	33.430	4.20	0.036
Time*Time	1	30.58	30.575	3.84	0.069
Temperature*Temperature	1	36.28	36.285	4.56	0.050
Error	15	119.31	7.954		
Total	19	813.03			

Table 5 Residual analysis of the developed prediction models for DCI

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	3	4391.9	1463.96	58.71	0.000
Linear	2	3750.4	1875.18	75.20	0.000
Time	1	138.4	138.40	5.55	0.032
Temperature	1	3612.0	3611.95	144.85	0.000
Square	1	726.4	726.38	29.13	0.000
Temperature*Temperature	1	726.4	726.38	29.13	0.000
Error	16	399.0	24.94		
Model	3	682.13	227.378	53.26	0.000
Linear	2	660.37	330.185	77.34	0.000
Time	1	138.84	138.843	32.52	0.000
Temperature	1	521.53	521.526	122.16	0.000

Square	1	20.18	20.175	4.73	0.045
Time*Time	1	20.18	20.175	4.73	0.045
Error	16	68.31	4.269		
Model	3	254.869	84.956	44.77	0.000
Linear	2	234.969	117.485	61.91	0.000
Time	1	3.709	3.709	1.95	0.181
Temperature	1	231.260	231.260	121.87	0.000
Square	1	23.739	23.739	12.51	0.003
Temperature*Temperature	1	23.739	23.739	12.51	0.003
Error	16	30.362	1.898		
Model	2	239542	119771	1104.32	0.000
Linear	2	239542	119771	1104.32	0.000
Time	1	5535	5535	51.03	0.000
Temperature	1	234007	234007	2157.62	0.000
Error	17	1844	108		
Model	3	431.409	143.803	166.76	0.000
Linear	2	427.938	213.969	248.12	0.000
Time	1	2.272	2.272	2.63	0.124
Temperature	1	425.666	425.666	493.61	0.000
Square	1	5.870	5.870	6.81	0.019
Temperature*Temperature	1	5.870	5.870	6.81	0.019
Error	16	13.798	0.862		
Total	19	445.207			

3.1. Performance Model Development and Analysis

Regression Equation in Uncoded Units for hardness

The equation for the hardness is

$$H = -1774 + 0.494\, x_2 + 4.263\, x_1 + 0.01105\, x_2^2 - 0.002283\, x_1^2 - 0.001972\, x_2 * x_1 \quad (7)$$

Model Analysis of hardness for 0.56%C-Steel

The regression equation in equation 7 is a full quadratic equation consisting of the holding time, austenitizing temperature, the squares of holding time and austenitizing temperature and the interaction term showing the product of time and temperature.

Regression Equation in Uncoded Units for Impact Strength of 0.56%C-Steel

$$Impact\ (J) = -513 + 0.1317\, x_2 + 1.335\, x_1 - 0.000820\, x_1^2 \quad (8)$$

The regression equation in equation 8 has a square term that is the square of temperature and it has a quadratic term but not a full quadratic model.

Regression Equation in Uncoded Units

$$Tensile\ strength = -15490 - 5.38\ x^2 + 35.45\ x_1 + 0.0699\ x_2^2 - 0.01857\ x_1^2 \quad [9]$$

The regression equation in equation 9 includes square terms of the two factors but the interaction term is not included and it is a linear plus squares type of equation with quadratic terms but a full quadratic model.

Regression Equation in Uncoded Units

$$\%R.I.A = -640 - 0.894\ x_2 + 1.346\ x_1 + 0.01346\ x_2^2 - 0.000614\ x_1^2 \quad [10]$$

The regression equation in equation 10 includes square terms of the two factors but the interaction term is not included hence it has quadratic terms but not a full quadratic model.

Regression Equation in Uncoded Units

$$\%E = -208.5 - 1.662\ x_2 + 0.3071\ x_1 + 0.00204\ x_2{*}x_1 [11]$$

The regression equation in equation 11 has an interaction term in addition to the linear term that is the product of holding time and austenitizing temperature. It has a quadratic term but not a full quadratic model.

Model Summary Table for Grade 1 Steel

Table 6 Model summary table for the response of grade 1 steel

Response	S	R-sq	R-sq(adj)	R-sq(pred)
Hardness	5.11216	93.86	91.66	87.68
Impact	4.72032	75.87	71.34	65.75
U.T.S	2.37716	98.64	98.28	97.63
%E	5.95145	94.80	93.82	90.91

The model summary table in table 6 portrays that the R-sq value and the R-sq (adj) are within 4 percent close to the other. R-sq (pred) shows high values of more than 50% this shows that the model is highly adequate. The R-sq value of 93.86 states that the developed model made explanation of up to 93.86% variations in the data. The R-sq explains the accuracy of the prediction by the model.

Model Adequacy Measures: Figure 1 (a-d) shows the residual plots for all the responses.

3.1.1 Model Adequacy Measure

Figure 1 shows four plots in one diagram which are normal probability plot, residual vs fit plot, residual vs order plot and frequency vs residual plot. Normal probability plot is used in testing for the normality of the data and when the distribution of the residuals resembles a straight line, then the data passes the normality test hence the normality test is passed for grade 1 Steel. Residual vs fits plot is used in testing for the constant variance assumption, if the plot does not show any pattern this means that the constant variance assumptions is satisfied. Grade 1 Steel does not show any pattern hence the model has passed this test. Residual vs order plot is used in testing for the independence of order assumption and if the plot does not show any pattern then the model does not depend on the form in which the data is presented hence the model has passed this test. Histogram of frequency vs residual shows the frequency of occurrence of residuals a lack of pattern in the shape of this histogram further proves the adequacy of this model. The model having passed all these tests can be certified adequate as a valid representation of the relationship that exist between austenitizing temperature, holding time and the grade 1 steel been given this heat treatment.

3.1.2 Analysis of Grade 2 Steel

Regression Equation in Uncoded Units

$$TENSILE\ STRENGTH = -724.6 + 0.6574\, x_1 + 2.2145\, x_2 \quad [12]$$

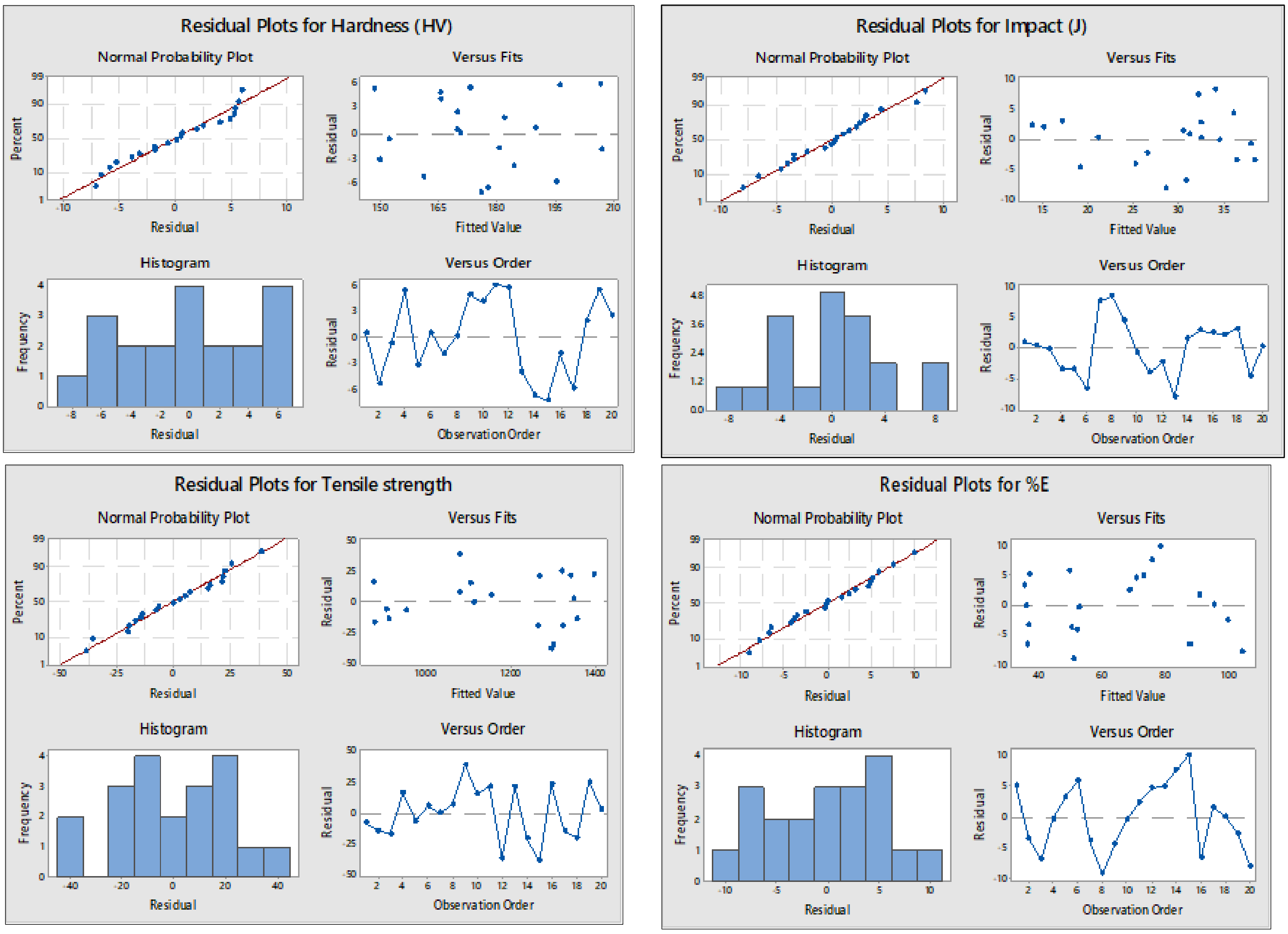

Figure 1 A-D Residual plots of the standardized effects for grade 1 Steel

The mathematical model in equation 12 is a linear equation showing only holding time and austenitizing temperature.

Regression Equation in Uncoded Units

$$HARDNESS = -112.9 - 2.563\, x_2 + 0.3891\, x_1 + 0.02670\, x_2^2 \quad [13]$$

The regression model in equation 13 has a square term portraying that it is the square of time with a quadratic term even though not a full quadratic model.

Regression Equation in Uncoded Units

$$\%R.I.A = -310.1 + 0.00039\, x_2 + 0.728\, x_1 - 0.000358\, x_1^2 \quad [14]$$

The regression model in equation 14 has a square term meaning it is the square of temperature that has a quadratic term but not a full quadratic model.

3.1.3 Regression Equation in Uncoded Units

$$\%ELONGATION = 27.93 - 0.248\, x_2 + 0.02226\, x_1 + 0.000263\, x_2{*}x_1 \quad [15]$$

The model equation in equation 15 is a linear model including an interaction term showing the product of holding time and austenitizing temperature.

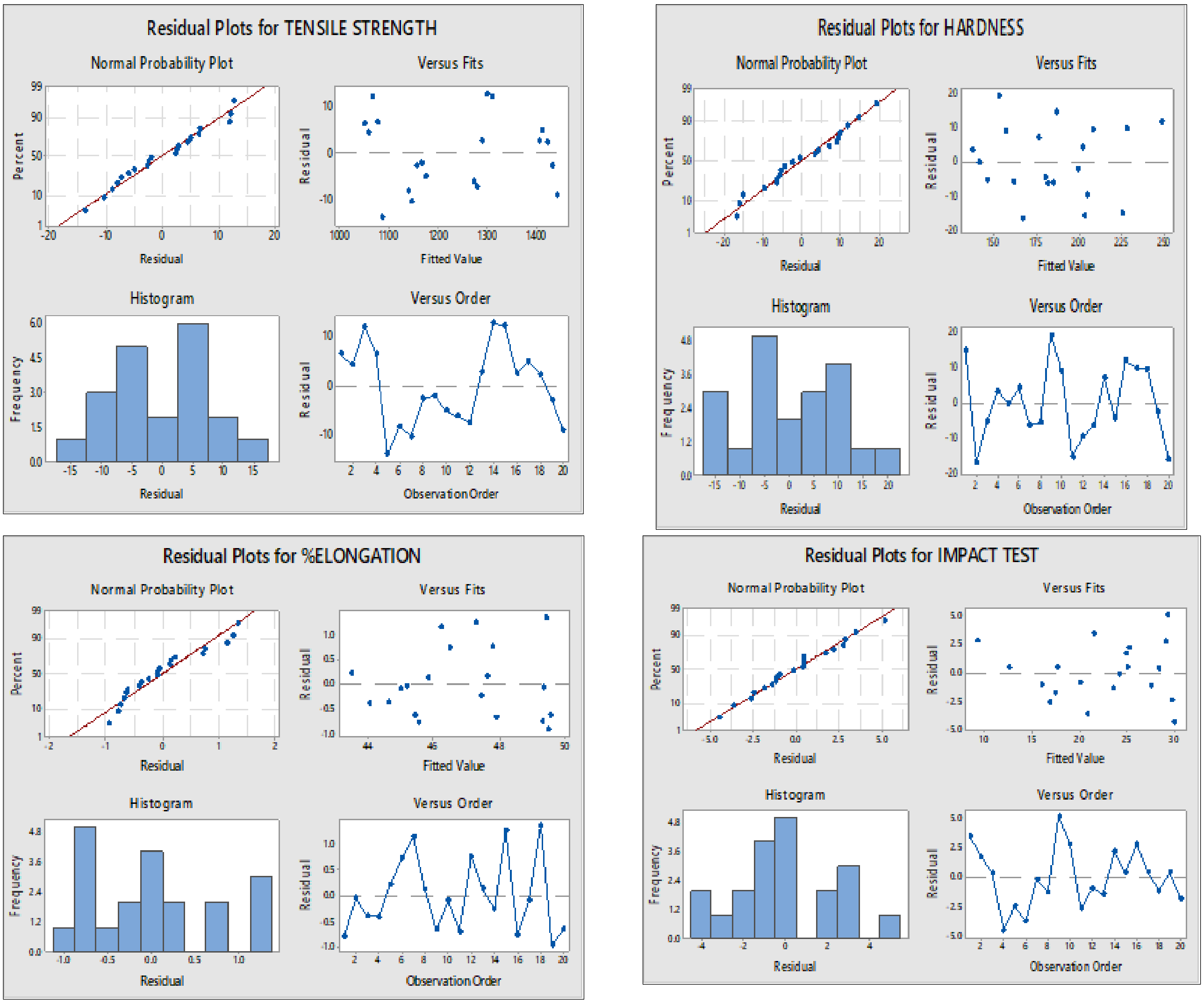

Figure 2 A-D Residual plots of the standardized effects for grade 1 Steel

Regression Equation in Uncoded Units

$$IMPACT\ TEST = -297 + 0.411\, x_2 + 0.790\, x_1 - 0.00400\, x_2^2 - 0.000493\, x_1^2 \quad [16]$$

The model equation in equation 16 is almost quadratic with only two square terms but has no interaction term hence it is partially quadratic.

Model Adequacy Measures: Figure 2 (a-d) shows the residual plots for the responses.

The normality test is passed for grade 2 Steel from figure 2. Grade 2 Steel does not show any pattern hence the model has passed the constant variance test. The model has passed the independence of order assumption test. The lack of pattern in the shape of the histogram further proves the adequacy of the model. The model hence is adequate for expressing the relationship between austenitizing temperature, holding time and the grade 2 steel that was austempered.

Model Summary Table

Table 7 The model summary table for the responses of grade 2 steel

Response	**S**	**R-sq**	**R-sq(adj)**	**R-sq(pred)**
Hardness	1.14836	89.49	87.49	82.93
Impact	2.82031	85.32	81.41	75.50
U.T.S	8.34296	99.68	94.64	99.54
%E	0.77050	88.41	86.24	81.00

Table 7 explains that R-sq and the R-sq (adj) are 4 percent close. R-sq (pred) with high values more than 50% means the model is highly adequate.

Analysis of DCI

Regression Equation in Uncoded Units

$$HARDNESS = -1667 - 0.1325\,x_2 + 4.104\,x_1 - 0.002206\,x_1^2 \quad [17]$$

The regression equation in equation 17 is not a full quadratic model.

Regression Equation in Uncoded Units

$$IMPACT\ STRENGTH = 102.64 + 0.3441\,x_2 - 0.08424\,x_1 - 0.00325\,x_2^2 \quad [18]$$

The regression equation in equation 18 is not a full quadratic model.

Regression Equation in Uncoded Units

$$\%\ elongation = -303.0 - 0.0217\,x_2 + 0.758\,x_1 - 0.000399\,x_1^2 \quad [19]$$

The regression equation in equation 19 is not a full quadratic model.

Regression Equation in Uncoded Units

$$Tensile\ strength = -488.3 + 0.838\,x_2 + 1.7843\,x_1 \quad [20]$$

The regression equation in equation 20 is a linear model with no square term.

Regression Equation in Uncoded Units

$$\%\ reduction\ in\ area = -165.0 + 0.0170\,x_2 + 0.425\,x_1 - 0.000198\,x_1^2 \quad [21]$$

The regression equation in equation 21 is not a full quadratic model.

Model Adequacy Measure

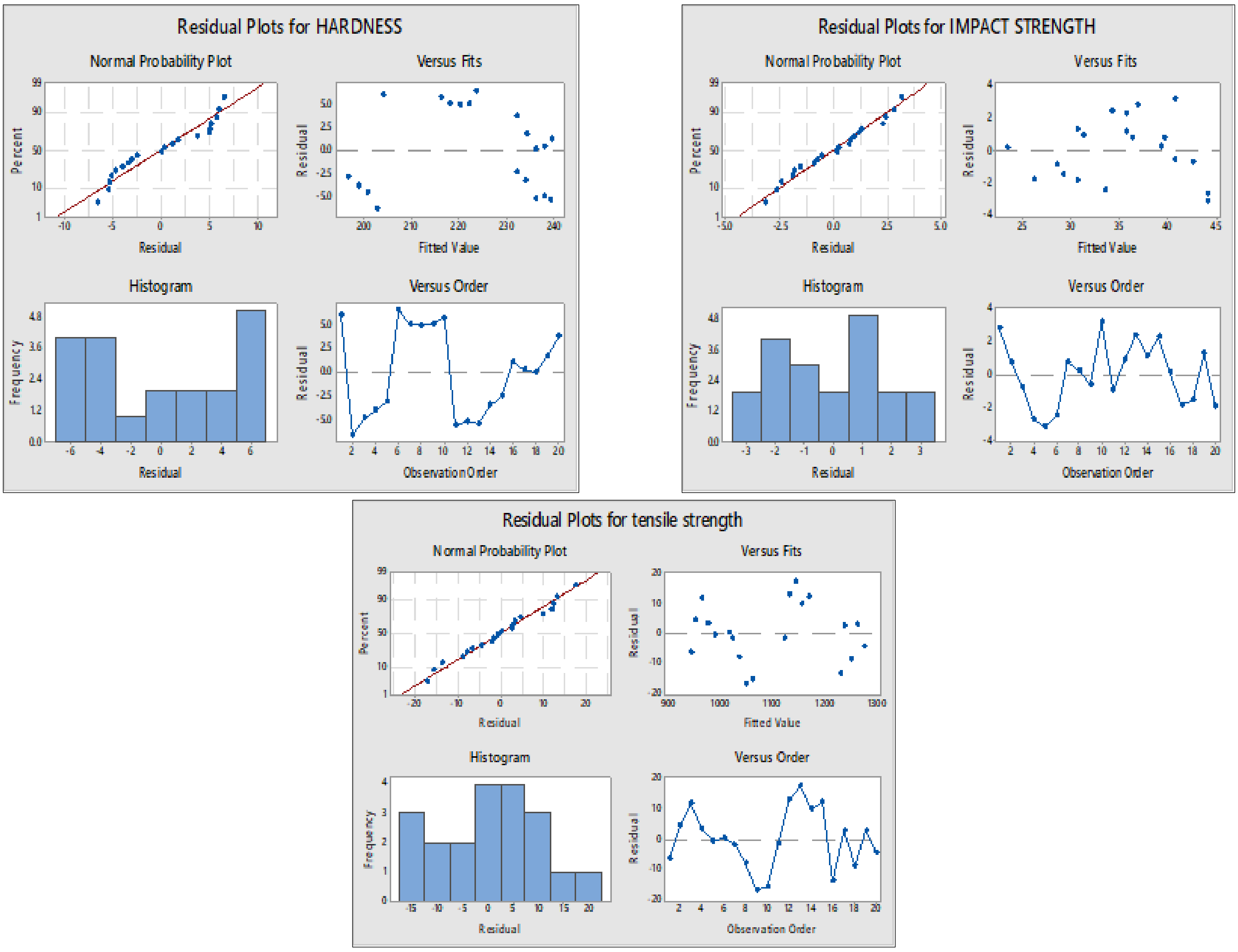

Figure 3 A-D Residual plots of the standardized effects for grade 1 Steel

The diagram in figure 3 shows the normality test is passed for DCI. DCI does not show any pattern hence the model has passed the constant variance test. The model passed independence of order assumption test since the plot did not show any pattern as seen in figure 3. Lack of pattern in the shape of this histogram proved the adequacy of the model. The model was found adequate for representing austenitizing temperature, holding time and the DCI that was heat treated.

Model Summary Table

Table 8 The model summary table for responses of DCI

Response	S	R-sq	R-sq(adj)	R-sq(pred)
Hardness	4.99365	91.67	90.11	87.23
Impact	2.06618	90.90	89.19	84.36
U.T.S	1.04142	99.24	99.15	98.98
%E	1.37755	89.36	87.36	82.90

Table 8 portrays that R-sq value and R-sq (adj) are 4 percent close. R-sq (pred) is highly adequate

3.2. Optimal values of austempered steel and DCI

The optimal values of the responses for the two grades of steel and ductile cast iron were done using desirability function approach as in Figure 4 (a-c).

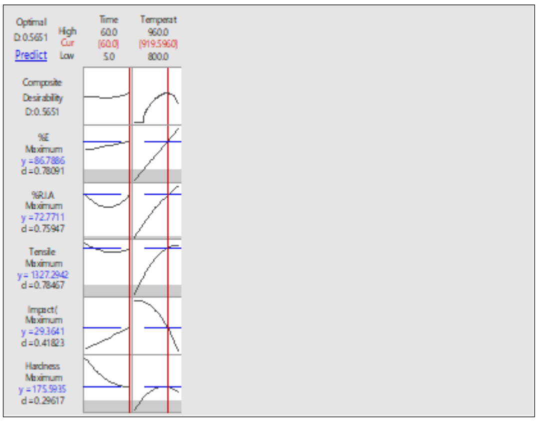

Figure 4a DFO for grade 1 steel

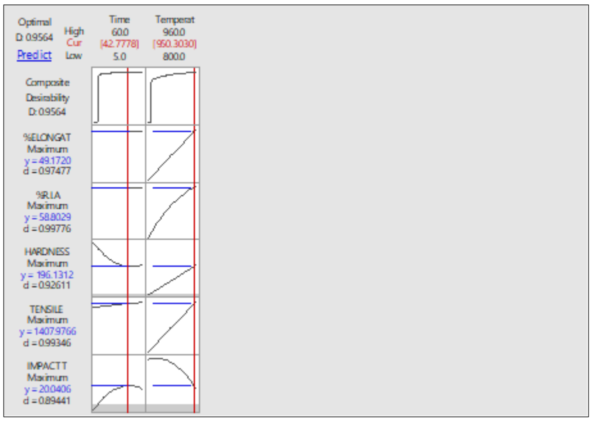

Figure 4b DFO for grade 2 steel

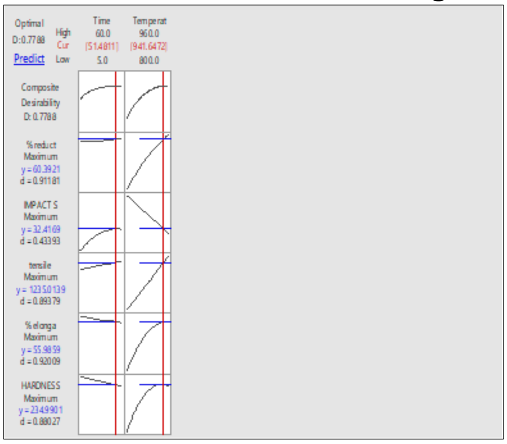

Figure 4c DFO for DCI

The developed simulation predicted optimal in uncoded factors (Figure 4a-c) has these optimal conditions 1327.29MPa, 29.36J, 72.77%, 86.79% and 175.59HRCfor 0.56%C-Steel; 1407.97MPa, 20.04J, 50.80%, 49.17% and 196.13 for 0.76%C-Steel; 1235.01MPa, 32.42J, 60.39%, 55.99% and 234.99HRC for DCI for quenching U.T.S, impact strength,% R.I.A, %E and hardness. This implies that as austenitizing temperature and holding time are increasing, the mechanical test also kept increasing until when those optimal conditions are meet and in agreement with [3].

3.3. Validation of the mathematical model

Table 9 Grade 1 steel validation

s/n	Response	Level predicted	Actual	GISMA and BS EN ISO 9223 standard	%error
1	U.T.S	1327.2942	1344.61	≥1100Mpa	1.2
2	Impact	30.4748	31.96	>20J	4.6
3	Hardness	175.5935	178.73	>150HRv	1.7
4	Poison's ratio	0.80366	0.83486	≥0.3 and <1	3.7

Table 10 Grade 2 steel test result

s/n	Response	Level predicted	Actual	GISMA and BS EN ISO 9223 standard	%error
1	U.T.S	1407.9766	1407.2	≥1150Mpa	-0.055
2	Impact	20.0406	20.15	>20J	4.7
3	Hardness	196.1312	197.05	>170HRv	0.4
4	Poison's ratio	0.823621	0.83621	≥0.3 and <1	1.5

Table 11 Austempered DCI test result

s/n	Response	Level predicted	Actual	GISMA and BS EN ISO 9223 standard	%error
1	U.T.S	1235.0139	1239.85	≥1000Mpa	0.3
2	Impact	32.4169	31.95	>20J	1.4
3	Hardness	234.9901	235.91	>150HRv	0.3
4	Poison's ratio	0.526773	0.536773	≥0.3 and <1	1.8

Table 9 to 11 portrays experimental validation for the two grades of steel and austempered ductile cast iron carried out on the responses with the percentage error for all the responses within ±5% signifying that the result is validated. Comparative analysis of these predictions with experimental values of austempered steel and ductile cast iron developed from this optimal design revealed prediction error of −0.055 to 1.8% and the measured parameters conformed to GISMA and BS EN ISO 9223 specifications.

3.4. Cost benefit analysis

Table 12 Costs incurred during austempering of steel and DCI

Quenchants	Heat treatment price @foundry 30mm × 250mm #	Selling price to malikwu company (cutting tool production company @Nnewi Anambra State) #	Savings (₦)	% Profit
B-PKO @15:85	3500	4500	1000	28.5%
B-PKO @20:80	4000	4500	500	12.5%
B-PKO @30:70	4300	4500	200	4.65%

Cost analysis in Table 12 displays price for austempering of steel with blend of B-PKO @15:85 saving about one thousand naira (#1000), B-PKO @20:80 saved five hundred naira (#500) and B-PKO @ 30:70 saved two hundred naira (#200) which translates to 28.57%, 12.5% and 4.65% profit. Blend of bitumen palm kernel oil @15:85 saved highest amount of money signifying that it is cost effective.

4. Conclusion

A simulation Models for performance test of process parameters of steel (0.56%C-Steel, 0.76%C-Steel) and DCI were developed. The performance tests of steel and DCI explained that process parameters of the steel and DCI are related to their austenitizing process in such a way that improving one affects the other. The CCD of two factors and five mechanical properties is carried out using austenitizing temperature and holding time as the design factors. This study revealed that austenitizing temperature and holding time of 916.5^{0}C and 5 min are the optimal operational parameters of austempered steel and austempered DCI. ANOVA stated that the main effects of all the factors influenced the response variables significantly with the quadratic effect and factor interactions established for model adequacy and desirability. Performance analysis of the two grades of steel shows that the responses has these optimal conditions 1327.29MPa, 29.36J, 72.77%, 86.79% and 175.59HRC for 0.56%C-Steel; 1407.97MPa, 20.04J, 50.80%, 49.17% and 196.13 for 0.76%C-Steel; 1235.01MPa, 32.42J, 60.39%, 55.99% and 234.99HRC for DCI for quenching U.T.S, impact strength,% R.I.A, %E and hardness. This implies that as austenitizing temperature and the holding time increases, the responses kept increasing until when those optimal conditions were meet and in agreement with [3]. B-PKO @15:85 saved about one thousand naira (#1000), B-PKO @20:80 saved five hundred naira (#500) and B-PKO @ 30:70 saved two hundred naira (#200) which translates to 28.57%, 12.5% and 4.65% profit. Bitumen palm kernel oil @15:85 saved greater amount of money signifying that it is cost effective. Hence, adoptions of the developed empirical mathematical models are recommended in automobile and engineering industries during heat treatment operations.

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