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Simulation of Austenitising Temperature and Quench Time for Application Specific based Austempering of Carbon Steels in B-PKO Medium

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ABSTRACT: Simulation models for predicting of austenitising temperature and quench time for attaining desired properties of medium and high carbon steels during their austempering with bitumen-palm kernel oil quenching medium were developed in this study in order to march the process outputs with their proposed applications. The models were developed using response surface method with grade of carbon steel been processed and the hardness, ultimate tensile strength, impact strength, percentage elongation and area reduction desired of it after austempering constitute their predictors. The developed models and their terms exhibited P-values of are less than 0.05 and overall insignificant lack of fit status implying over 95% prediction accuracy. The function analysis revealed that main effects and some interactions of these predictors as well as quadratic effect of hardness influence the austenitising temperature and quench time required to achieve any given set of carbon steel's properties with this heat treatment process significantly. Thus, the simulations are recommended for effective logistic planning and advancement in medium and high carbon steel processing sector.

KEY WORDS: Austempering, austenitising temperature, carbon steel, model, prediction, quench time.

I. INTRODUCTION

Steel is the strongest and most important alloy available to mankind due to its wide-ranging engineering applications [1]. It basically made of iron with less than 2.14% carbon and varying traces of one or more other elements such as manganese, silicon, sulphur, phosphorus and oxygen [2, 3]. This alloy's unique feature of altering physical and mechanical properties with varied mix of iron/carbon/other elements content and heat treatment methods lend it to diverse construction applications [1, 2].Steel is of four basic types as tool, alloy stainless and carbon steels [3]. BigRentz [4] showed carbon steel as the cheapest and most adaptable/ideal for numerous purposes due to its strength, durability and relatively absence of other elements in its makeup. The three subgrades of carbon steel are low, medium and high carbon steel with carbon content range of 0.015 - 0.30%, 0.31 - 0.60% and 0.60 - 2% respectively [4]. Low carbon steel is highly ductile while the medium and high are higher strength and toughest varieties respectively but less ductile [2, 4]. Thus, the need to make the medium and high carbon more flexible by improving their ductility to allow for the metals effective working operations such as deep drawing, cold forging and machining without distorting their wear-resistance characteristics lend them to austempering heat treatment [3, 5].Austempering is an isothermal ferrous metals'hardening process used for producing bainite microstructure as desired in medium to high carbon steels in order to improve their ductility, toughness, strength and resistance to shock as well as reduced distortions [2, 6]. Bodycote [6] indicated that austempering of medium to high carbon steels is basic for hardening them within the range of 35-55 HRC when maximum flexibility and toughness as well as distortion reduction are required. This heat treatment process involves heating the part to a temperature within the austenitising range (790-950°C) and quenchingitin a bath of a medium held at a constant temperature of 250-450°C for some time to allow transformation to a bainite microstructure before cooling to room temperature [6, 7].Hence,Smallman and Ngan[7] and Nwankwojike *et al*. [8] reported austenitising temperature, quenchant and quenching timeas major determinants of austempering process output settings.

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The quest for locally available, cheapnontoxic and environmental friendly quenching media with maximum cooling capacity and minimum distortion in dimensions and cracking during quenching prompted unending evaluation of cooling potentials of several fluid [9, 10]. Effective moderation of heat transferred during quenching was revealed as a way of minimizing the distortion and cracking by [11] while a throwback on [12] showed efficacy of aqueous polymer solutions and oils in minimizing temperature differences between different areas of steel parts during quenching. Hence, the recent evaluation of quenching potentials of bitumen by [13, 14] and that of some vegetable oils by [9, 15, 16]. The merits of blending a polymer and vegetable oil for austempering medium and high carbon steel was also explored by using bitumen and palm kernel oil blend by [8]. Although, [17] and [18] confirmed the effectiveness the bitumen-palm kernel oil blend over other locally sourced quenching media and simulated the mechanical properties of medium and high carbon steels austempered with it, none of the models developed predicts the process austenitising temperature and quench time. These works gave mathematical functions relating hardness, ultimate tensile strength, impact strength, percentage %elongation and %area reduction of the austempered carbon steel with austenitising temperature and quench time of the process as predictors which is the reverse of practical requirement in steel production. In addition, the optimal blending ratios predicted in these works are not application specific. The actual interest of steel manufactures is known the austenitising temperature and quenches time that will yield a given/desired set of properties after austempering given steel material with a known quenching medium before processing. Simulation of this temperature and quench time as functions of desired mechanical properties the steel will attain after the heat treatment will enable processing of its raw metal in turn with intended specific applications. Since this will aid effective logistic planning in this sector, mathematical models for predicting austenitising temperature and quench time required for austempering any given medium and high carbon steel materials with bitumen-palm kernel oil quenchant in turn with end user's desires were developed in this study.

II. METHODOLOGY

The study involve development of austenitising temperature (T) and quench time (t) models for austempering medium and high carbon steel in accord with desired properties/intended applications of the output metal using bitumen-palm kernel oil quenching medium. The model predictors include hardness (H), ultimate tensile strength (U), impact strength (I_e), percentage elongation (E) and area reduction (A) of the austempered metals. The data used for fitting the functional relationship between these predictors and austenitising temperature/quench time (responses) were obtained from experimental records of [8, 17] and organized as shown in table 1 for desirability response functions simulation. The criteria adopted for selecting the best fit model for each of the two process parameters under study are that a good mathematical model must exhibit less than 0.05 P-values, small SS of Error, R^2 and adjusted R^2 values close to 1(100%) with less than 0.2 difference, ANOVA-$F_{cal} > F_{tab}$ and insignificant lack-of-fit. Others include that normal probability and histogram of a good function's residuals must approximate straight line and dumb-bell plots while their residuals versus run order and residuals versus fitted response plots remain structureless (scatter feature).

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Table 1: Profile of austenitising temperature/quench time with mechanical properties of austempered carbon steels

Factors						Responses	
Grade of Steel (%C)	**UTS (MPa)**	**Hardness (HRC)**	**Impact Energy (J)**	**Elongation (%)**	**Area Reduction (%)**	**Temperature (^oC)**	**Time (min)**
0.56	946.10	250.98	32.11	42.10	40.11	800.00	5.00
0.76	1056.8	260.51	25.63	44.77	44.01	800.00	5.00
0.56	1136.20	190.51	21.13	70.32	69.12	900.00	5.00
0.76	1229.58	206.18	14.16	47.23	56.11	900.00	5.00
0.56	1417.11	170.11	16.18	81.15	83.15	960.00	5.00
0.76	1407.2	201.01	12.06	48.57	58.82	960.00	5.00
0.56	900.12	201.81	32.82	33.21	30.21	800.00	15.00
0.76	1061.27	238.12	26.63	45.13	44.11	800.00	15.00
0.56	1214.06	178.73	24.21	60.21	59.13	900.00	15.00
0.76	1270.98	175.16	19.17	48.54	56.58	900.00	15.00
0.56	1340.30	155.71	17.21	92.37	74.27	960.00	15.00
0.76	1416.16	149.21	12.99	49.28	59.02	960.00	15.00
0.56	863.51	180.43	34.32	29.50	26.55	800.00	30.00
0.76	1078.71	960.33	28.72	44.24	44.15	800.00	30.00
0.56	1188.69	840.63	20.38	56.16	57.11	900.00	30.00
0.76	1290.96	155.35	22.15	47.77	56.61	900.00	30.00
0.56	1301.73	130.06	20.21	65.21	69.24	960.00	30.00
0.76	1423.35	800.22	14.85	50.78	59.16	960.00	30.00
0.56	894.65	170.99	32.95	35.60	33.62	800.00	45.00
0.76	1083.2	197.05	25.54	43.65	43.06	800.00	45.00
0.56	1245.15	170.41	31.96	63.15	61.12	900.00	45.00
0.76	1330.79	171.97	32.16	47.21	55.02	900.00	45.00
0.56	1344.61	800.71	14.41	97.11	97.17	960.00	45.00
0.76	1428.16	140.52	18.07	48.57	58.91	960.00	45.00
0.56	909.60	140.63	34.89	38.63	36.41	800.00	60.00
0.76	1072.6	187.01	27.40	43.71	44.14	800.00	60.00
0.56	1356.45	160.56	45.23	66.45	64.21	900.00	60.00
0.76	1355.07	165.29	25.54	48.54	56.62	900.00	60.00
0.56	1351.63	146.35	21.23	96.25	78.23	960.00	60.00
0.76	1431.79	140.38	15.36	48.95	58.13	960.00	60.00

III. RESULTS AND DISCUSSION

The best fit models developed from the experimental records for predicting austenitising temperature and quench time required for austempering medium and high carbon steels as desired for different/specific applications are as follows;

$$T = 1442 - 968G - 0.25U - 0.41H - 8.14I_e + 142E - 231A + 0.00022H^2 + 0.62GH + 0.0044UI_e + 0.00014UH \quad (1)$$

$$t = -70.70 + 194.7G - 5.32U - 0.32H + 3.76I_e + 1.11E - 1.15A + 0.00073H^2 - 0.28GH - 0.012HI_e \quad (2)$$

The fit statistics of these models (table 2 and 3) depicts their compliance to independence or constant variance assumption which implies adequate estimation/approximation of austenitising temperature and quench time of the austempering process under study with them. This is because their valued R^2 are close to one while the differences between their predicted and adjusted R^2 are less than 0.2. In addition, the functions and their terms exhibited P-values of are less than 0.05 and overall insignificant lack of fit status. The suitability of the functions for these responses' prediction is also obvious in their residual plots (fig.1 and 2) which featured the straight line and dumb-bell profiles expected of a good model's normal probability and histogram. The residuals versus fits points fall randomly on both

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sides of the center line with no recognizable pattern in each case while their residuals versus order plots are of random pattern. The models' survey showed that main effects and some interactions of these predictors as well as quadratic effect of hardness influence the austenitising temperature and quench time required to achieve any given set of carbon steel's properties with this heat treatment process significantly. Thus, the developed models are apt for simulating austempering heat treatment process of medium and high carbon steel with bitumen-palm kernel oil quenching medium.

Table 2: Fit statistic of the austenitising temperature model

Source	DF	Adj SS	Adj MS	F-Value	P-Value	SS	R	Adj-R^2	Pred-R^2	LOF
Model	***8***	***129261***	***16157.7***	***241.46***	***0.000***	***8.18031***	***98.92%***	***98.91%***	***98.93%***	***Insignificant***
G	1	10766	10765.7	160.88	0.000					
U	1	18986	18986.1	283.72	0.000					
H	1	63	62.6	0.94	0.044					
I_e	1	3055	3055.1	45.65	0.000					
E	1	16	15.76	0.39	0.007					
A	1	28	27.97	0.69	0.017					
H^2	1	458	457.7	6.84	0.016					
GU	1	1545	1545.2	23.09	0.000					
UH	1	275	275.3	4.11	0.035					
UI_e	1	300	299.9	4.48	0.046					
Error	21	1405	66.9							
Total	29	130667								

Table 3: Fit statistic of the quench time model

Source	DF	Adj SS	Adj MS	F-Value	P-Value	SS	R	Adj-R^2	Pred-R^2	LOF
Model	***8***	***9229.7***	***1153.7***	***9.35***	***0.000***	***11.1063***	***98.79%***	***98.74%***	***98.78%***	***Insignificant***
G	1	157.7	157.7	1.28	0.001					
U	1	4.7	4.713	0.16	0.012					
H	1	689.8	689.8	5.59	0.028					
I_e	1	1125.3	1125.3	9.12	0.007					
E	1	872.7	872.7	7.07	0.015					
A	1	654.5	654.5	5.31	0.032					
H^2	1	5475.2	5475.2	44.39	0.000					
GH	1	872.0	872.0	7.07	0.015					
HI_e	1	3884.9	3884.9	31.50	0.000					
Error	21	2590.3	123.3							
Total	29	11820.0								

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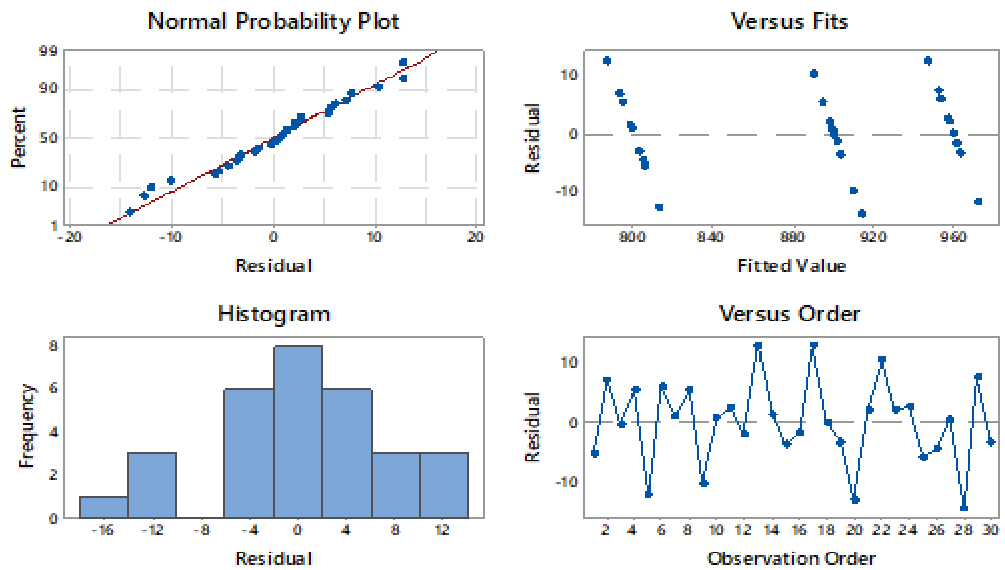

Fig. 1: Residual plots of the austenitising temperature model

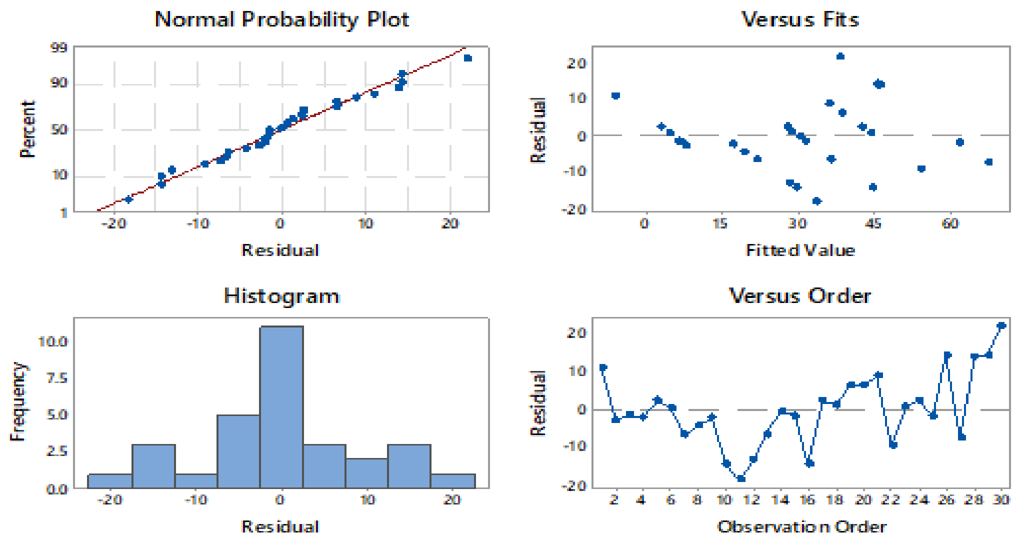

Fig. 2: Residual plots of the quench time model

IV. CONCLUSION AND FUTURE WORK

Mathematical models for predicting of austenitising temperature and quench time for attaining desired properties of medium and high carbon steels during their austempering with bitumen-palm kernel oil quenching medium were developed in this study in order to march the process outputs with their proposed applications. The functions and their terms exhibited P-values of are less than 0.05 and overall insignificant lack of fit status implying over95% prediction accuracy and therefore recommended for effective logistic planning and advancement in medium and high carbon steel processing sector. Development of software for implementing the models developed in this study is also recommended.

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