VOL. 05 NO. 5,
AUGUST, 2024
E-ISSN 3027-1339
P-ISSN 3026-8257

African Scholar Publications & Research International
www.africanscholarpub.com

Journal of Systematic, Evaluation and Diversity Engr. (JSEDE)

Effect of Austempering Process Parameters on the Mechanical Properties of Mild Steel Quenched in a Mixture of Used Engine Oil and Ash

Onyemelikeya Ifeoma Blessing; Okigbo Nonso Emmanuel; & Nwumeh Onyeka Francis
Department Of Mechanical Engineering, Federal Polytechnic Oko

Abstract
The study was aimed at enhancing the utilization of a blend of recycled engine oil and ash as an appropriate quenchant for the austempering heat treatment of mild steel. The objectives of the study were to utilize Response Surface Methodology to create a model for efficient use of the mixture as a quenchant, determine the optimal process parameters (time and temperature) for austempering with the mixture and develop a predictive model to guide the austempering process in achieving specific desired properties in mild steel. The experimental was designed with Minitab resulting to 27 experimental runs. The independent variables were temperature and time to determine the hardness, impact energy and maximum load. The result showed that maximum hardness of 190BHN, impact energy of110J and maximum load of 6500W. The optimization studied gave hardness value of 176.870, impact energy of 60.1852 and maximum load of 5964.81 at temperature of 870^0C and time of 27.7773mins with desirability of 1. It was concluded from the studies that using the optimal austempering time and temperature for achieving specific mechanical properties suitable for a particular application can save cost of production by reducing energy cost.

Keywords: Austempering, Mechanical properties, Mild steel, Engine oil, Ash

Introduction
The use of mild steel in various industrial applications, such as automotive and construction, has increased the demand for high-performance steels with improved mechanical properties. One method for improving the mechanical properties of mild steel is through the austempering process, which involves heating the steel to a specific

temperature and then quenching it in a liquid medium. The quenching medium used in this process can have a significant impact on the final mechanical properties of the steel.

Austempeing process is the same both in steel and cast iron. However, it produces baintic structure in steel while in cast iron, it yields a structure of acicular ferrite and high carbon, stabilized austenite known as ausferrite (Chima*et al.*,2020). The design of austempering process in steel which produces bainitic structure yields properties that combine uniform and consistent hardness with toughness. This gives rise to high resistance to brittle fatigue. Other advantages of the bainitic structure include higher ductility, increased strength at a given hardness, increase toughness, greater fatigue life and less distortion (Igwemezie andAgu, 2014).

In order to achieve any transformation in austempering heat treatment in steel, the microstructure of the metal must be austentite structure. The initial process involves austenitizing at temperature ranges of 7900 C – 9500 C (Steel, 1995; Rajan*et al,* 1998). This facilitates transformation that yields austenite structure**.** The heat treated material is held at the same temperature for a specific time range in order to produce a full and uniform austenitic metal structure with consistent carbon content (Rajan*et al,* 1998). The holding time depends on the nature of the alloy and the process undertaken. Quenching at a very fast cooling rate is necessary to prevent the formation of pearlite but should be above martensitic temperature so that the microstructure is a control mixture of bainite and martensite. However, the dominating phase should be more of bainite. The severity of the quenching media depends on its ability to mediate heat transfer at the heat interface during quenching. According to ASM International (1991) and Totten (2006), the cooling rate and the holding time are important factors required to achieve the desired micro structure.

The temperature and time used in the austempering process vary depending on the desired properties and intended application. The bainitic holding time determines the microstructure of the steel, which can include various mixtures of bainite, martensite, and retained austenite (Mohamed, 2017). The microstructure, which is characterized by platelets of ferrite separated by regions of residual austenite or other phases such as martensite or cementite, is greatly affected by the process parameters and the composition of the alloy (Rajan et al., 1998). These factors can influence nucleation and grain growth, and ultimately affect properties such as tensile strength, yield strength, toughness, and hardness. A higher transformation temperature requires less time for the bainitic reaction to be completed and ensures a uniform distribution of carbon atoms, which leads to a homogenous structure (Rajan et al., 1998). Many studies have been conducted to investigate the impact of heat treatment variables on the microstructure evolution of heat treated steel, which in turn determines the material's properties (Golanski, 2013; Shresthai*et al.* 2015). Ferrous alloys with different chemical compositions respond differently to various heat treatment parameters, resulting in different microstructures with specific mechanical properties. Therefore, it can be concluded that the microstructure of metal determines its mechanical properties (Abioye*et al.*, 2017).

Mild steel is widely used in a variety of industries and applications, each requiring different properties that can be achieved through heat treatment. The specific process parameters used in austempering have a significant impact on the properties of the resulting mild steel. The

choice of quenchant is a key factor in this process, as the interaction between process parameters and desired properties can vary depending on the quenchant used. A blend of used engine oil and ash, which is a readily available waste product in Africa, is a commonly used quenchant in the region. However, the interaction between this quenchant and the process parameters of austempering needs to be further studied in order to provide guidance for local.

LITERATURE REVIEW

MILD STEEL

Mild steel, also known as low carbon steel is a type of steel that is commonly used in various industries because of its properties such as malleability, ductility and ease of welding. Furthermore it is relatively inexpensive than other types of steel. Mild steel is composed mainly of iron, carbon and small amounts of other elements such as manganese, sulphur and phosphorus. However, it does not possess the same strength as high carbon steel, but it is more resistant to corrosion.

TABLE 2.1 PHYSICAL PROPERTIES OF MILD STEEL

Density (Mg m^{-3})	Young Modulus (GPa)	Yield Strength (MPa)	Tensile Strength (MPa)	Melting point
7.9	210	220	430	1535°C

HEAT TREATMENT OF STEEL

The present discussion is confined to the metastable phasediagram of the system, because of the obvious reason thata very long time is taken by the system to attain the stable state. The information about the different phases present at different temperaturecomposition combination maybe obtained from the above equilibrium diagram. It may benoted that, A_1, the lower critical temperature denotes theminimum temperature up to which austenite(γ) can be present; A_3, is the upper critical temperature describing theequilibrium between g and ferrite(a); whereas A_{cm}, is the linedescribing the solubility of carbon in γ. Quite often the suffixesc, e, and r are used with the critical temperatures. For example,A_{c1} denotes the temperature at whichγforms from ferriteduring heating. Its equilibrium counterpart is written as Ae1,whereas Ar1 stands for γ to ferrite transformation duringcooling. Similar meanings are assigned to Ac_3, A_{e3}, A_{r3}, A_{ccm},A_{ecm}, and A_{rcm}. Addition of alloying elements tend to alterthe position of A_1 and A_3 lines; at the same time it changes the eutectoid composition which is 0.8 wt.%C in pure binary Fe–C alloy. The alloying elements added in iron–carbon system are classified broadly in to two types:One group of alloying elements is known to stabilize ferrite; these alloying elements are called ferrite stabilizers andin general the crystal structure of ferrite stabilizing elementsis body centered cubic (BCC). Cr, Mo, W, Nb, etc. are someexamples of ferrite stabilizer.Similarly, the elements stabilizing austenite are calledaustenite stabilizer. The austenite stabilizers are mainly thosewith face centered cubic (FCC) crystal structure; Cu, Mn, Ni, C,etc. are austenite stabilizers.If ferrite stabilizing elements are added to steel, there will berise in A_1 and A_3 temperatures, which restrict the austenitephase field; on the other hand the addition of γ stabilizingelements will depress A3 and A1 lines in the equilibrium diagram. The effect of

commonlyused alloying elements on A1 temperature and eutectoid carbon content is shown in Fig 2

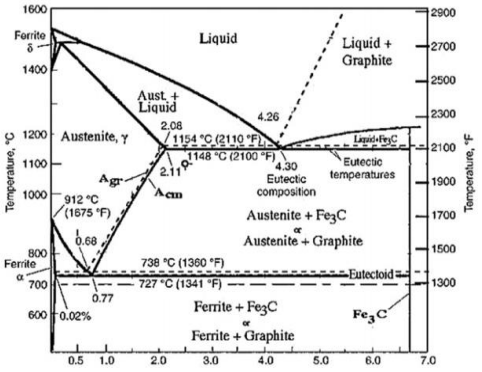


Fig 1 Combined iron–graphite and Fe–Fe3C phase diagram showing steel panel up to 2.11 wt.% carbon.

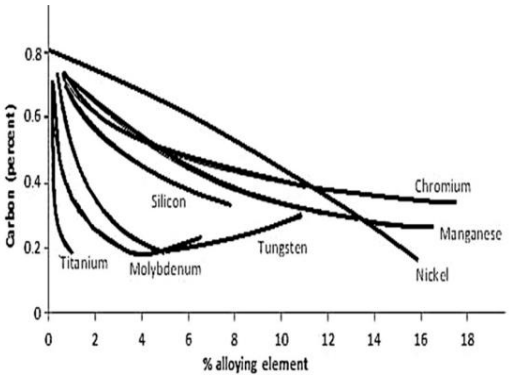


Fig 2 Effect of alloying element on the carbon content of the eutectoid composition.

As stated earlier the prediction of equilibrium phase diagram is of limited use in practicalheat treatment processesexcept for annealing, which attempts to achieve equilibrium.

AUSTEMPERING

Austempering is a special kind of heat treatment, in which austenite transforms into lower bainite. Generally, in conventional heat treatments, the austenitic structure transforms into pearlite or martensite during the continuous type of cooling regimes. Generally, the process is carried out following these steps: Heating steel above austenitizing temperature, quenching in a bath (generally salt bath) at a constant temperature above the Martensite Start($M_{S)}$ temperature of particular steel (200-400°C), waiting in the bath until the bainitic transformation is completed, and finally cooling the steel piece to room temperature by air or any other desired method and cleaning. In literature, sometimes the austempering process is referred to as isothermal quenching or isothermal hardening due to the isothermal heating regime of the process. Austempering is a hardening process which yields desirable mechanical properties including higher ductility, toughness, and strength for a given hardness. Resistance to shock, Reduced distortion, specifically with thin parts.

During austempering holding at the austempering temperature eliminates thermal stresses andisothermal transformation of austenite tolower bainite in a salt bath also protects the steel from oxidation due to neutral atmosphere and from distortion dueto prevailing situation of hydrostatic pressure. Austemperingproduces lower bainite which is composed of supersaturatedferrite and e carbide (Figure 53). Needless to say that aftercompletion of bainitic transformation no other transformation takes place during cooling toroom temperature frombainitic reaction temperature. The low temperature tempering of hardenedsteel also produces low carbon martensite (i.e., ferrite of low supersaturation)and ε carbide. However

strength and toughness properties ofaustempered material are much better than the hardened andtempered material. During austempering lower bainitic transformation isenvisaged. This means that quenching to austempering temperature leads to the formation ofsupersaturated ferrite bydiffusionless shear transformation mechanism.

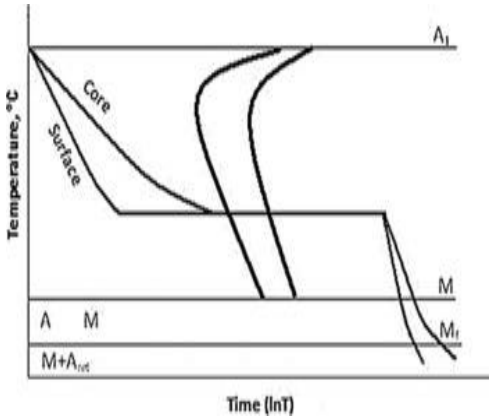


Fig 3 Austempering

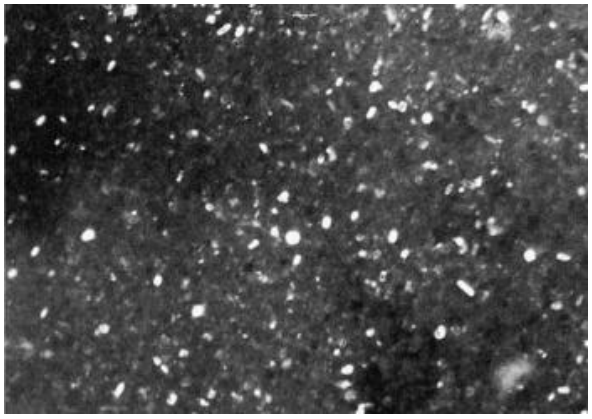


Fig 4 Microstructure Showing Supersaturated Carbide and Ferrite

But due to thehigh temperature and also due to great urge for getting relievedfrom super saturation, the ferrite rejects carbon quite quickly inthe form of ε carbide of 8.3 wt.%C (Reed-Hill R.E).Lower bainiticferrite is much lean in carbon content as compared to theaustenite and so excess carbon is rejected by the growing bainitic ferrite crystals ahead of the interface between the productferrite phase and the parent austenite phase. Thus austeniteahead of bainitic ferrite becomes enriched with carbon; thisprocess of formation of bainitic ferrite and continuous carbonenrichment of austenite ahead of interface continues, till a timeis reached when high carbon austenite ahead of growing ferritecrystal cannot give way to the formation of bainite; at this time,growth of bainitic ferrite stops and there remains high carbonaustenite, which cannot even transform to martensite duringsubsequent cooling to room temperature, owing principallyto its increased metastability. Such a large amount of austeniteretained inevitably due to incomplete bainitic reaction providesadequate ductility to the alloy. Thusaustempering enables toachieve a good combination of high strength and high toughness, which otherwise would not have been possible, if thesame steel was fully hardened and then tempered at the sameaustempering temperature Fig 5. Austempering can harden complicated steelcomponents without causing distortionand cracking. It can impart excellent toughness and ductility inthin sections of plain carbon steel. However, the entire crosssection of the steel must be cooled rapidly enough to miss thenose of the IT curve. It is to note that thicker sections (43 mm)of plain carbon steels are difficult to be austempered because ofthe short incubation period at the nose of TTT diagram. So,only thin sections are subjected to austempering. Howeverlarger sections of alloy steels can be austempered where thetime to start the transformation is quite high.

Austempering is primarily used to harden medium to high carbon steels in the range of 35-55 HRC when toughness is required with the additional benefit of a reduction in distortion. The process is widely used in the automotive industry for clips and other parts where maximum flexibility and toughness are required. The range of austempering applications generally encompasses parts fabricated from sheet or strip of small cross section. Austempering is particularly applicable to thin section carbon steel parts requiring exceptional toughness.

Practical Factors Affecting Successful Austempering

In addition to the effect of composition and section thickness of the components, the practical factors like austenitizing temperature and holding time at austempering temperature and time, furnace atmosphere, etc., are of utmost importance.

A. Austenitization: As the austempered hardness is high enough, only finish machining is to be carried out after austempering. Care must be taken to avoid surface decarburization and scaling during high-temperature austenitizing. Suitable process includes austenitization in salt bath, controlled atmosphere furnace, fluidized beds, or employing some scale resistant coating on the casting surface. The temperature distribution in the furnace should be homogeneous otherwise failure to austenitization and distortion of the castings are caused. Variation in the temperature can arise from the incorrect stacking of the charge, poor process control, and inadequate furnace design. Austenitization is usually carried out within the temperature range of 850–950 °C. As the austenitization temperature is increased the equilibrium carbon content in the austenite will increase and this will ultimately affect the IT characteristics during austempering. With increase in 'C' content the martensite start temperature (Ms) is depressed and the bainite transformation time is delayed particularly at lower austempering temperature. It has been observed that, both tensile strength and yield strength are increased as the austenitization temperature is increased from 850 to 925 °C for one hour and austempered between 300 and 425 °C. Elongation is not affected by the change in austenitization temperature. Austenitizing time should be minimum necessary to homogenize the temperature throughout the cross-section and to saturate the austenite with equilibrium 'C' content. Austenitization time is also affected by the chemical composition, the austenitization temperature, and the nodule count.

B. Austempering: The ultimate mechanical properties of austempered iron depends on the microstructural parameters such as the bainite or ausferrite morphology, the volume percentage of retained austenite, and the presence of martensite. The formation of martensite is accentuated by the low austempering temperature with short holding time. Irons which have lower bainitic structure Fig. 5 yields higher strength and lower ductility than those with upper bainite. Lower bainite is typically formed at austempering temperature below about 330 °C and the transformation kinetics are influenced by chemical composition and the 'C' content in the austenite. The 'C' content in its turn is a function of austenitization temperature and time. Upper bainite is formed at isothermal treatment about 330 °C and below the pearlite formation temperature, i.e., 500 °C. Ductility and toughness of upper bainite structure

is much higher compared to lower bainite counterpart (Fig 6) but the hardness is lower in the former one. Another microconstituent present after austempering is retained austenite when austempering time ranges 0.5–3h. The amount of retained austenite is much higher (up to 40%) in the upper bainitic irons than that in lower bainitic irons (less than 10%).

C. ***Surface deformation treatments***: Improved fatigue properties can be achieved by the presence of a compressive residual stress at the surface in the components subjected to fatigue loads. The residual compressive stress can be introduced by shot peening or surface rolling. These cold working can cause an additional benefit to transform the retained austenite in ADI to strain-induced martensite. The strain-induced martensite formation is associated with 4% increase in volume which further cause the increment in compressive residual stress. The strain-induced martensite significantly improve the wear resistance.



Fig 5 Microstructures of Austempered Mild Steel at 300, 350 and 400

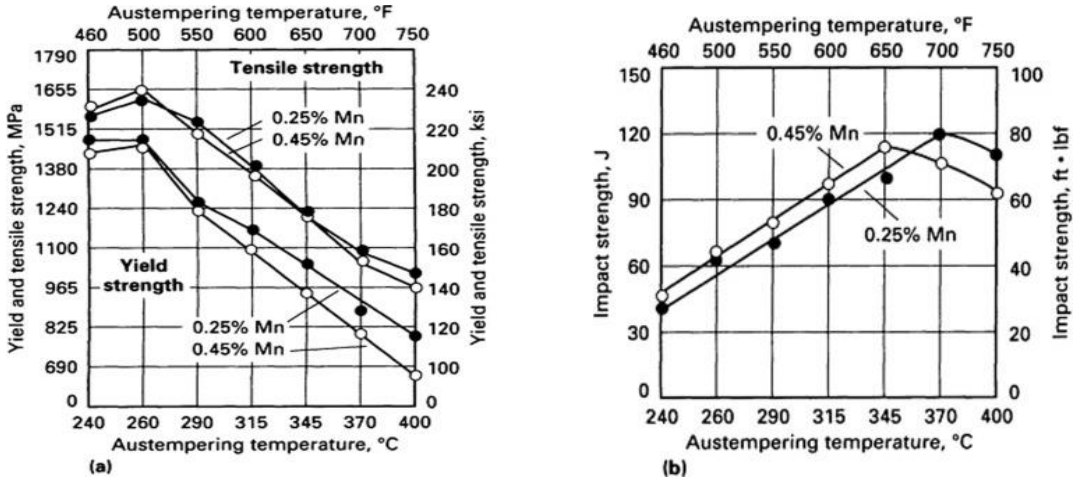


Fig 6 Effect of Austempering Temperature On The Properties Of Ductile Iron; (A) Yield And Tensile Strength Versus Austempering Temperature; (B) Impact Strength Versus Austempering Temperature.

QUENCHING

The process of quenching involves rapidly cooling a work piece using methods such as water, oil, polymer, air, or other fluids to achieve specific material characteristics. It prevents

unwanted low temperature changes such as phase transformations by reducing the time frame in which these reactions occur. This results in an increase in hardness by reducing the crystal grain size of both metallic and plastic materials.

A MIXTURE OF USED ENGINE OIL AND ASH AS QUENCHANT

Though using a mixture of used engine oil and ash as a quenchant is not a recommended practice. Engine oil is not a suitable quenchant for heat treatment of steel as it does not have the proper properties for cooling the steel at a controlled rate. Ash, on the other hand, is not a good coolant as it can cause cracking and other defects in the steel.

RESPONSE SURFACE METHODOLOGY

The origin of RSM is the seminal paper by Box and Wilson (1951)According to (Khuri, AI, Cornell, JA. *Response Surfaces*. 2nd ed.) response surface methodology (RSM) is a collection of statistical and mathematical techniques useful for developing, improving, and optimizing processes. It also has important applications in the design, development, and formulation of new products, as well as in the improvement of existing product designs. The most extensive applications of RSM are in the industrial world, particularly in situations where several input variables potentially influence some performance measure or quality characteristic of the product or process. This performance measure or quality characteristic is called the response. It is typically measured on a continuous scale, although attribute responses, ranks, and sensory responses are not unusual. Most real-world applications of RSM will involve more than one response. The input variables are sometimes called independent variables, and they are subject to the control of the engineer or scientist, at least for purposes of a test or an experiment. RSM is used in the development of an adequate functional relationship between a response of interest, y, and a number of associated control (or input) variables denoted by x1, x2, . . ., xk. In general, such a relationship is unknown but can be approximated by a low-degree polynomial model of the form.

$y = f(x)\beta + (1)$ …….. (1)

Wherex = (x1, x2, . . ., xk) andf (x) is a vector function ofp elements that consists of powers and cross- products of powers of x1, x2, . . ., xk up to a certain degree denoted by d (≥ 1), β is a vector of p unknown constant coefficients referred to as parameters, and is a random experimental error assumed to have a zero mean. This is conditioned on the belief that model (1) provides an adequate representation of the response. In this case, the quantity $f(x)\beta$ represents *the mean response, that is, the expected value of* y,*and is denoted by* $\mu(\mathbf{x})$.*Two important models are commonly used inRSM. They includethe first-degree model (*d = *1),*

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \epsilon$$

*and the second-degree model (*d = *2)*

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum \sum_{i<j} \beta_{ij} x_i x_j + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \epsilon.$$

The purpose of considering this model is threefold:

- To establish a relationship, albeit approximate, between y and x1, x2, . . . ,xk that can be used to predict response values for given settings of the control variables.
- To determine, through hypothesis testing, significance of the factors whose levels are represented by x1, x2, . . . ,xk.
- To determine the optimum settings of x1, x2, . . .,xk that result in the maximum (or minimum) response over a certain region of interest.

OBJECTIVES AND TYPICAL APPLICATIONS OF RSM

Response surface methodology is useful in the solution of many types of industrial problems. Generally, these problems fall into three categories (Fedorov V. Theory of Optimal Experiments *2009).*

- *Mapping a Response Surface over a Particular Region of Interest*. Consider theaustempering process as explained so far. Normally, this process would operate at a particularsetting of reaction time and reaction temperature. However, some changes to thesenormal operating levels might occasionally be necessary, perhaps to produce a product that meets other specific grade requirement. If the true unknown response function has been approximated over a region around the current operating conditions with a suitable fitted response surface say a second-order surface, then the processengineer can predict in advance the changes in yield that will result from anyreadjustments to time and temperature.
- *Optimization of the Response*. In the industrial world, a very important problem is determining the conditions that optimize the process. In the austempering process, this implies determining the levels of time and temperature that result in best mechanical properties.
- *Selection of Operating Conditions to Achieve Specifications or Customer Requirements*. In most response surface problems there are several responses that mustin some sense be simultaneously considered. For example, in the austempering process the mechanical properties considered include tensile strength, hardness and impact energy. A particular part may require specific properties in certain levels RSM can be used to determine the appropriate level of factors that can meet these specifications.

MATERIALS AND METHOD

MATERIALS

The materials used are:

1. Furnace
2. Hot Bath
3. Spectrometer

4. Buehler Metaserv 2000 Single Grinder PolisherBrinell Hardness Testing Machine
5. Buehler Metaserv 2000
6. Universal Testing Machine
7. Charpy Impact Test Machine

SOFTWARE REQUIREMENT

The software used in analysing the experimental data was Minitab. Minitab is a statistics package developed at the Pennsylvania State University by researchers Barbara F. Ryan, Thomas A. Ryan, Jr., and Brian L. Joiner in 1972. It began as a light version of OMNITAB, a statistical analysis program by NIST. Statistical analysis software such as Minitab automates calculations and the creation of graphs, allowing the user to focus more on the analysis of data and the interpretation of results.

METHOD

Experimental procedure

A total of 27 samples of uniformly cut mild steel rods were used for this experiment. The samples were divided into three groups of nines and charged into the furnace and then quenched in a quenching bathcontaining a mixture of used engine oil and ash ataustempering temperatures of 870°C, 910°C, 950°C and for 10, 20 and 30 minutes. A breakdown of the experiment is shown in the table below. The three groups were then tested for Impact Energy, Tensile Strength, and Hardness respectively.

Table 3.2 Summary of Experimental Parameters

Material	Austempering Temp (°C)	Austempering Time (Min)
	850	10
		20
		30
	910	10
MILD STEEL		20
		30
	950	10
		20
		30

Table 3.3 Samples Description

Sample	Temperature	Time
K	870	10
L	910	10
M	950	10
N	870	20
O	910	20
P	950	20

Q	870	30
R	910	30
S	950	30

THE MODEL SUMMARY TABLE

The model summary table give some important information about the model. It shows four important statistics that describes the model they are S-value,R-squared, adjusted R-squared, predicted R-Squared. S represents the standard deviation of the distance between the data values and the fitted values. It is used to assess how well the model describes the response. The lower the value of S the better the model, for all four responses the value of S is sufficiently low to indicate that the models describes the responses appropriatley.

The R-squared is the percentage of variation in the response that is explained by the model. The higher the R^2 value the better the model fits the data. The adjusted R^2 is the percentage of the variation in the response that is explained by the model, adjusted for the number of predictors in model relative to the number of observations. The adjusted R-squared value should be close to the R-squared value the difference between the two values should not be more than 4%.

From the response surface regression analysis summary tables we can see that the values of R-sqaured and R-squared adjusted are high an within 4% of each other.

Finally, the predicted R-squared is used to determine how well a model predicts the response for new observations. The higher the value the better the model is in predicting accurate response for new observation. For all the responses the predicted R-squared value is high enough to indicate the good ability to predict and also reasonably close to the R-squared value to indicate that the model is not over-fit.

METALLOGRAPHIC INVESTIGATION

The microstructural examination of the specimens was conducted using standard test techniques and a metallurgical microscope. The samples were rough ground using the Buehler Metaserv 2000 Single Grinder Polisher machine with grits of 60, 120, 400, and 600. The surfaces were made finer and smoother by using successively smaller grits. The samples were then polished with a 4-micron diamond paste abrasive and finished with emerald cloth on a rotating polishing wheel. The samples were etched for sixteen seconds in a solution of 3% nitric acid and 97% ethanol (3% nital) and the microstructure was then characterized by observing the samples under an AP2000MTI metallurgical microscope. Micrographs were captured at a magnification of X100

RESULTS AND DISCUSSIONS

Experimental results

The experimental design for the blending of the recycled engine oil and ash as an appropriate quenchant for the austempering heat treatment of mild steel was analysed and presented in figure 1. The result showed the effects of temperature and time on the hardness of the oil

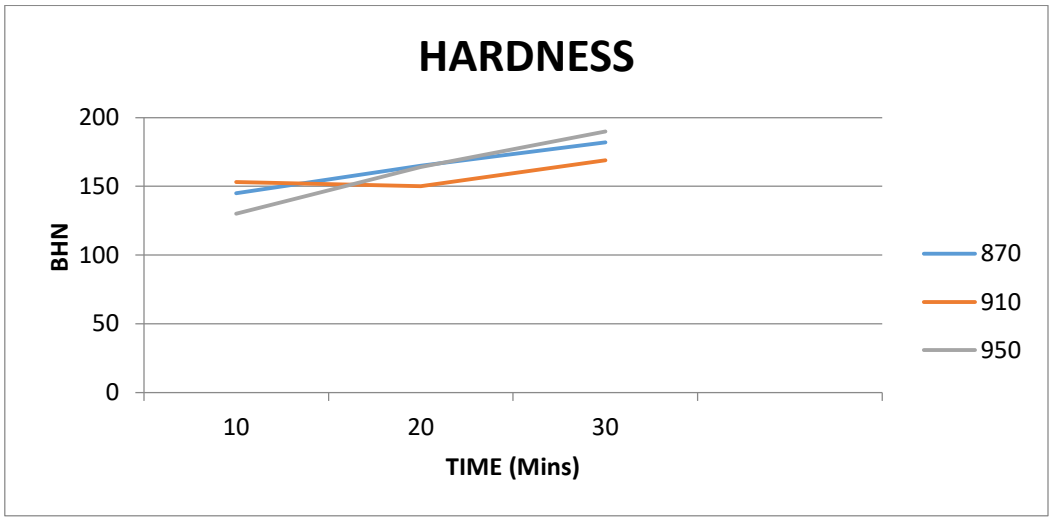


Figure 4.1: Effect of time and temperature on hardness

Effect of Time

Martensite is a very hard and strong phase of steel that is formed when the steel is cooled quickly. The higher the temperature is, the more carbon atoms can diffuse in the iron matrix, creating more martensite, which leads to a harder and stronger steel.

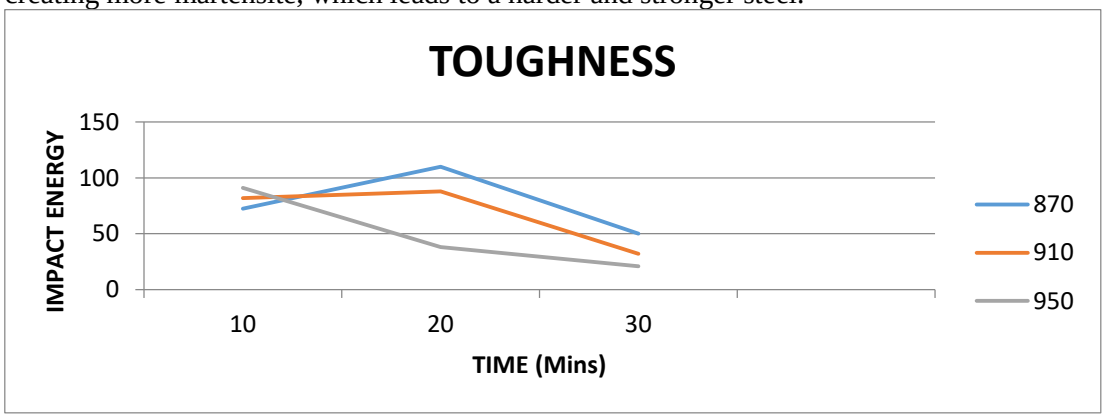


Figure 4.2: Effect of time and impact energy on Toughness

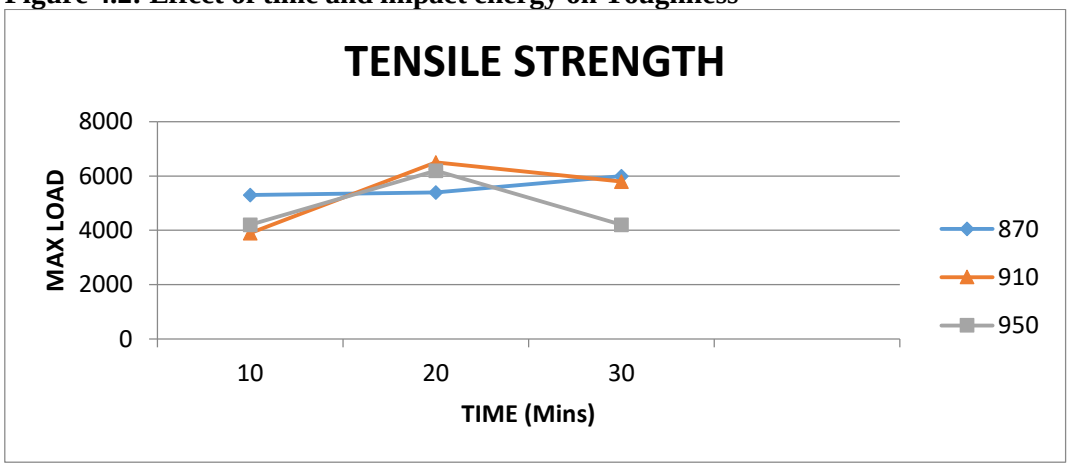


Figure 4.3: Effect of time and maximum on tensile strength

Effect of temperature

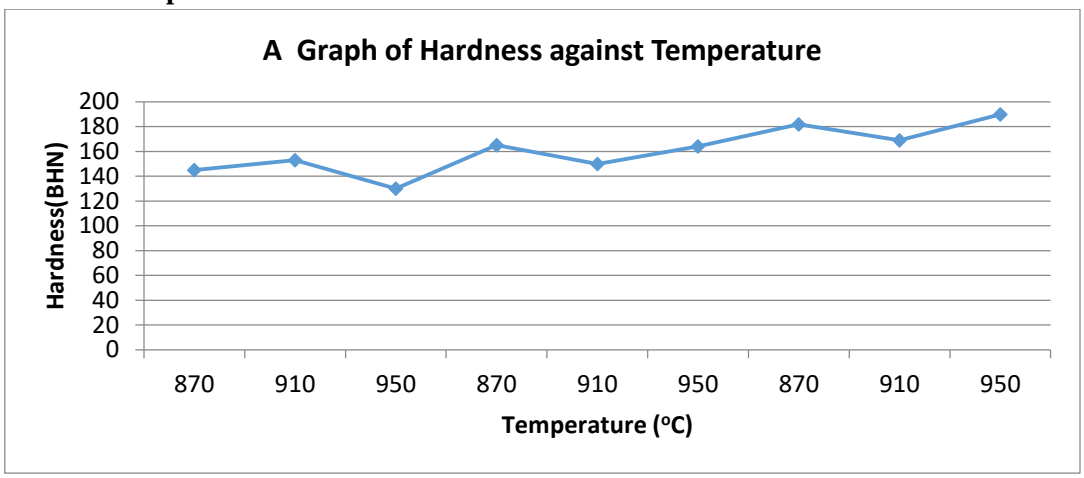


Figure 4.4: Effect of temperature on the hardness

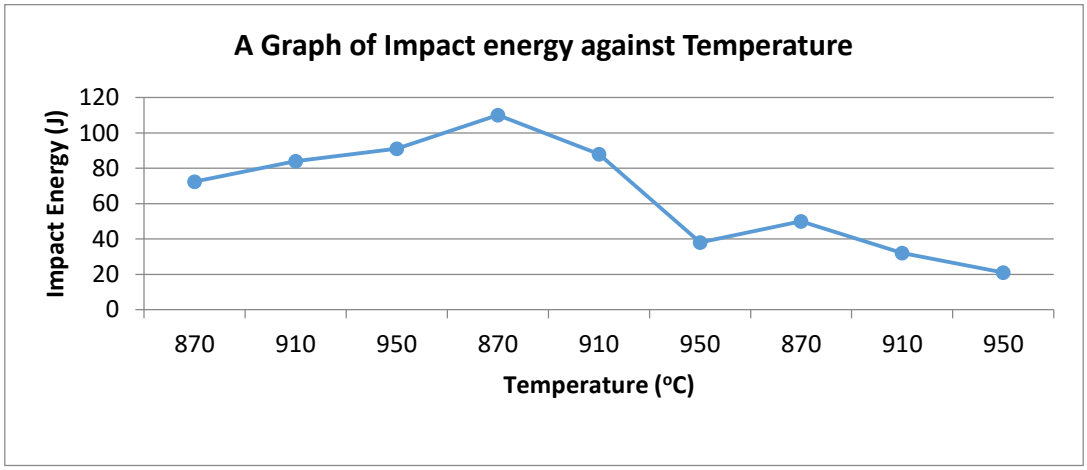


Figure 4.5: Effect of temperature on the impact energy

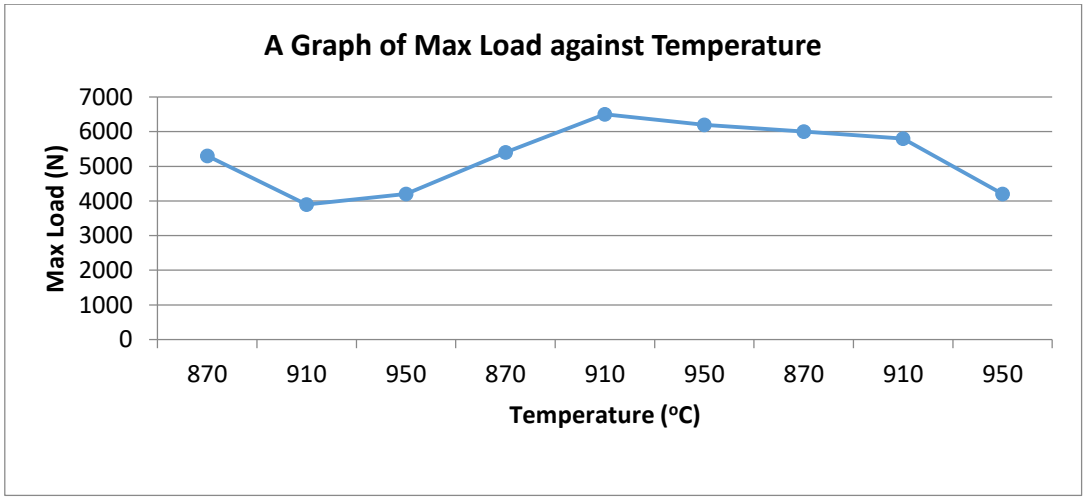


Figure 4.6: Effect of temperature on the maximum load

Response Surface Analysis Result

The experimental data for all twenty-seven samples were combined and analyzed using response surface regression in Minitab. The combine experimental data is shown in the table below.

Table 4.1: Experimental result

Temperature	Time	Hardness (BHN)	Impact Energy (J)	Max Load
870	10	145	72.5	5300
910	10	153	84	3900
950	10	130	91	4200
870	20	165	110	5400
910	20	150	88	6500
950	20	164	38	6200
870	30	182	50	6000
910	30	169	32	5800
950	30	190	21	4200

ANOVA Results

The table of coefficients shows the subset of predictor terms chosen by the stepwise process. It shows the constant value of the model equation and the coefficients of the predictor terms. For each of these terms it shows the S.E Coef, the T-value, the P-value and the VIF. These values convey information about each of the terms. The t-value is used to calculate the p-value and the p-value is used to test the null hypothesis. The p-value (test value) for these analysis is the same as the alpha value (0.15) of the stepwise procedure and any term whose value is less than or equal to the p-value is statistically significant while any term with a value greater than the p-value is statistically insignificant. As indicated in the stepwise procedure temperature and time must be included in the initial model even if they do not pass the p-value test.

The variance inflation factor (VIF) is used to detect whether one predictor has a strong linear association with the remaining predictors (the presence of multicollinearity among the predictors). VIF measures how much the variance of an estimated regression coefficient increases if your predictors are correlated (multicollinear).

VIF = 1 indicates no relation; VIF > 1, otherwise. The largest VIF among all predictors is often used as an indicator of severe multicollinearity. (Montgomery and Peck) suggest that when VIF is greater than 5-10, then the regression coefficients are poorly estimated. For all the responses no term has a VIF that is up to 2 which shows that there is no multicollinearity among the predictor terms hence the response surface regression coefficients are properly estimated.

Table of Coded Coefficients

Term	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant	153.6	95.9	(-4.7, 311.8)	1.6	0.16	
Temperature	-0.033	0.105	(-0.206, 0.140)	-0.32	0.761	1
Time	1.883	0.42	(1.191, 2.576)	4.49	0.004	1

Model Summary

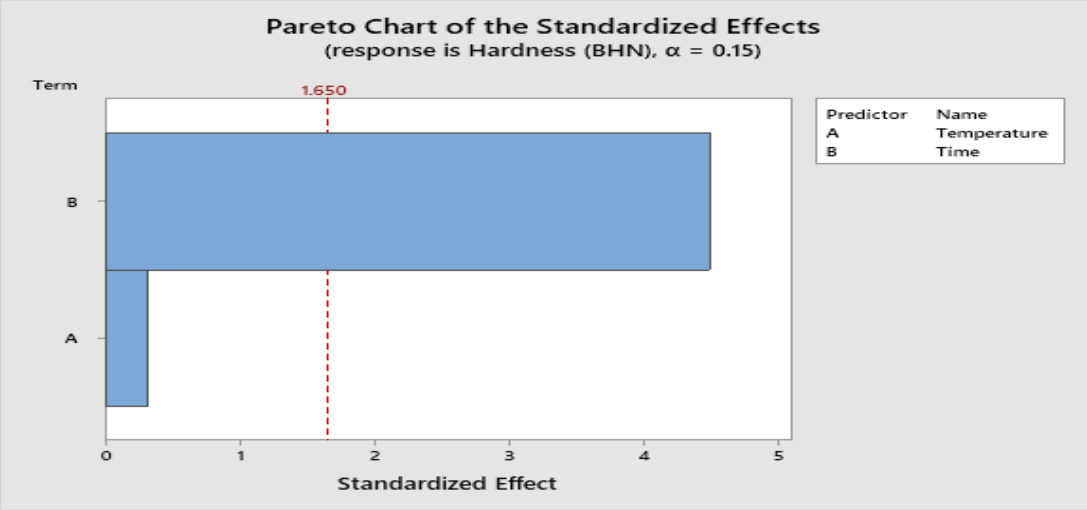
S	R-sq	R-sq(adj)	PRESS	R-sq(pred)	AICc	BIC
10.2799	77.13%	69.51%	1473.37	46.87%	81.84	72.62

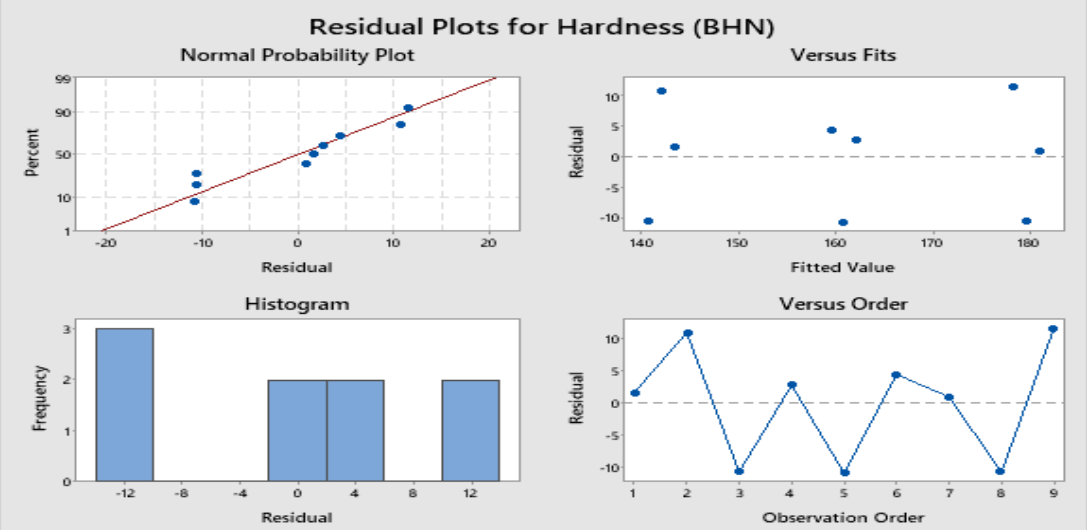
Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Regression	2	2138.83	77.13%	2138.83	1069.42	10.12	0.012
Temperature	1	10.67	0.88%	10.67	10.67	0.1	0.761
Time	1	2128.17	76.75%	2128.17	2128.17	20.14	0.004
Error	6	634.06	22.37%	634.06	105.68		
Total	8	2772.89	100.00%				

Regression Equation in Uncoded Units

Hardness (BHN) = 153.6- 0.033 Temperature - 1.883 Time





Effect of Impact Energy (J) on Temperature and Time

Coded Coefficients

Term	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant	-1771	8919	(-16927, 13386)	-0.2	0.85	
Temperature	4.5	19.6	(-28.9, 37.8)	0.23	0.828	6211.75
Time	-2.408	0.996	(-4.101, -0.716)	-2.42	0.06	1
Temperature*Temperature	-0.0027	0.0108	(-0.0210, 0.0157)	-0.25	0.815	6211.75

Model Summary

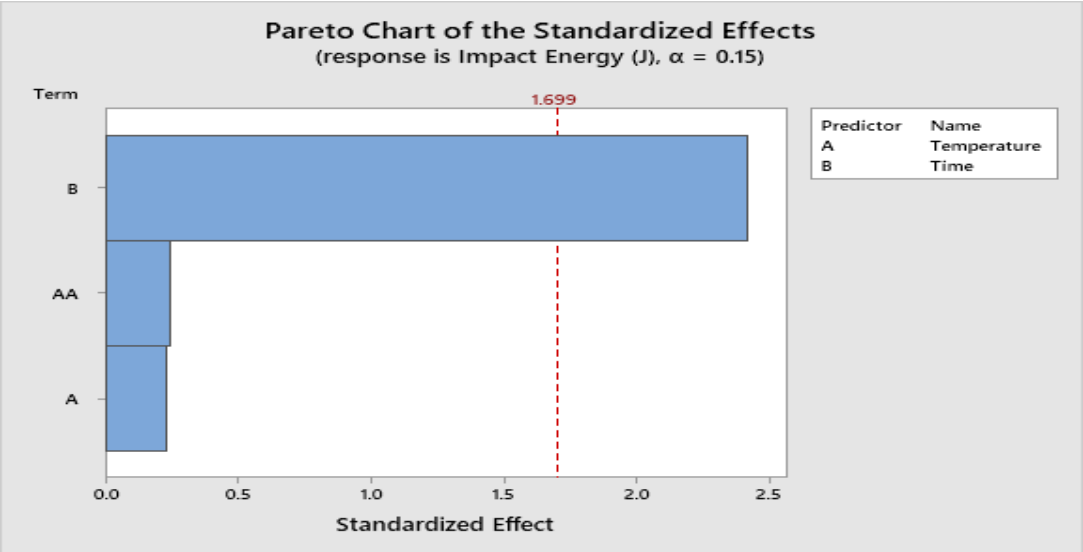
S	R-sq	R-sq(adj)	PRESS	R-sq(pred)	AICc	BIC
24.3945	60.98%	37.57%	9101.40	0.00%	107.75	88.74

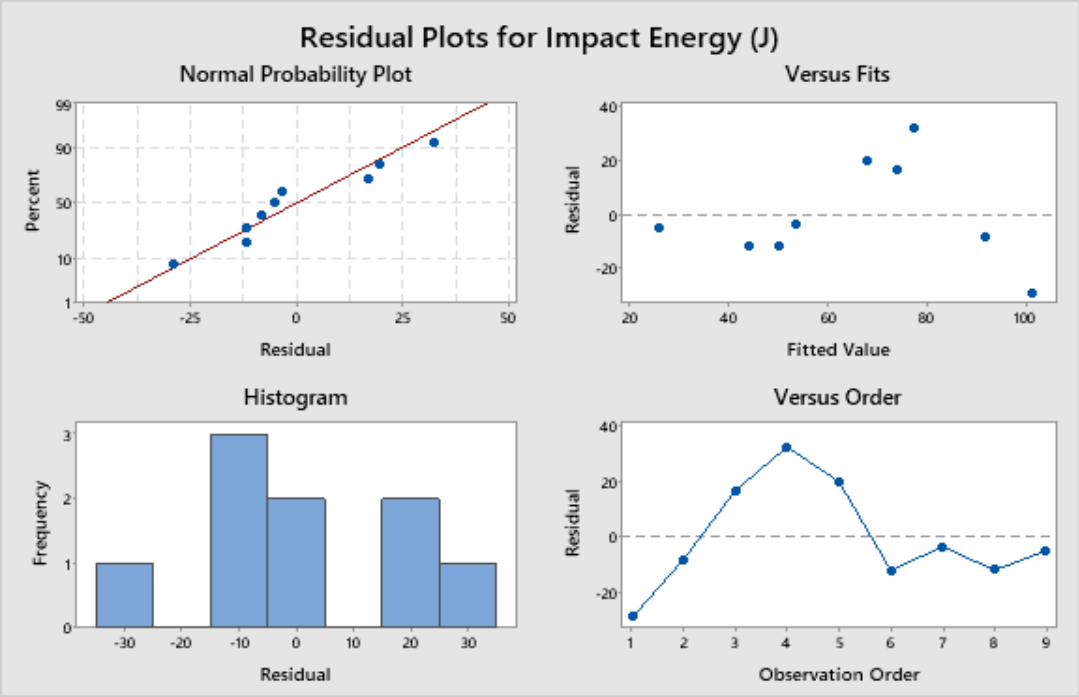
Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Regression	3	4650.54	60.98%	4650.54	1550.18	2.6	0.164
Temperature	1	1134.38	14.88%	31.17	31.17	0.05	0.828
Time	1	3480.04	45.53%	3480.04	3480.04	5.85	0.06
Temperature*Temperature	1	36.12	0.47%	36.12	36.12	0.06	0.815
Error	5	2975.46	39.02%	2975.46	595.09		
Total	8	7626	100.00%				

Regression Equation in Uncoded Units

$$\text{Impact Energy (J)} = -1771 + 4.5\text{Temperature} - 2.408\text{Time} - 0.0027\text{Temperature} * \text{Temperature}$$





Effect of Maximum Load versus Temperature, Time

Coded Coefficients

Term	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant	8596	7385	(-3954, 21146)	1.16	0.297	
Temperature	-8.75	7.83	(-22.06, 4.56)	-1.12	0.315	1
Time	497	219	(124, 869)	2.26	0.073	49
Time*Time	-11.33	5.43	(-20.56, -2.11)	-2.09	0.091	49

Model Summary

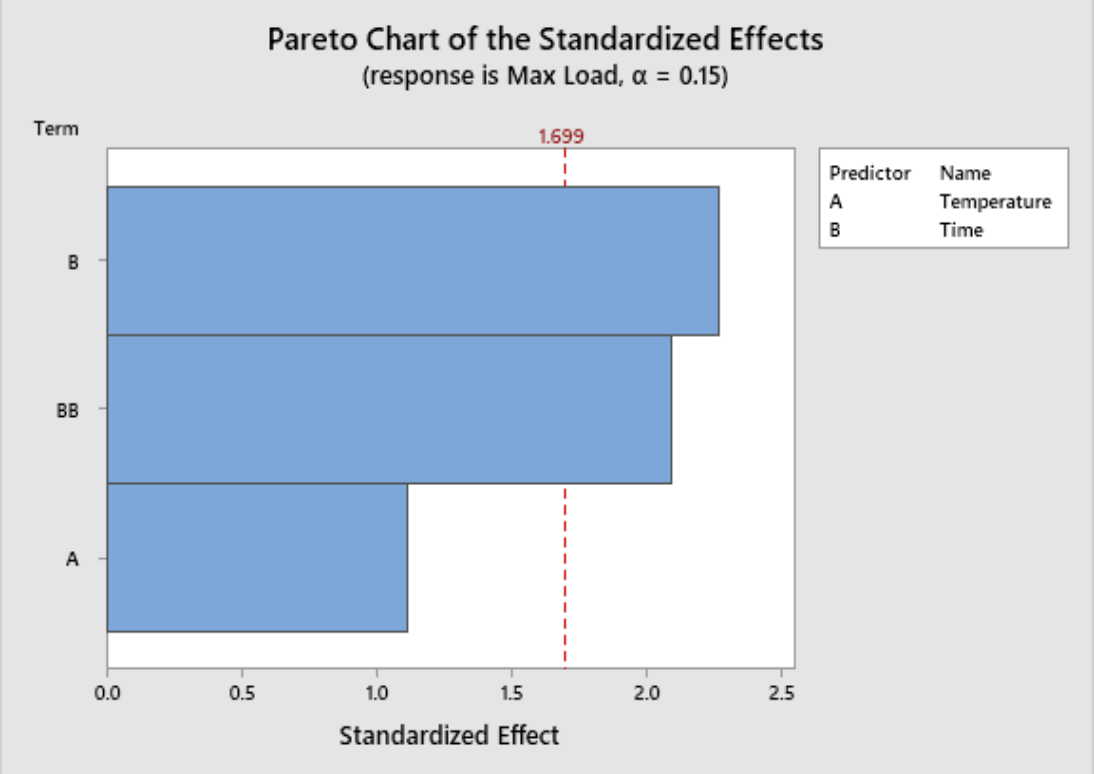
S	R-sq	R-sq(adj)	PRESS	R-sq(pred)	AICc	BIC
767.463	60.07%	36.11%	10455833	0.00%	169.83	150.81

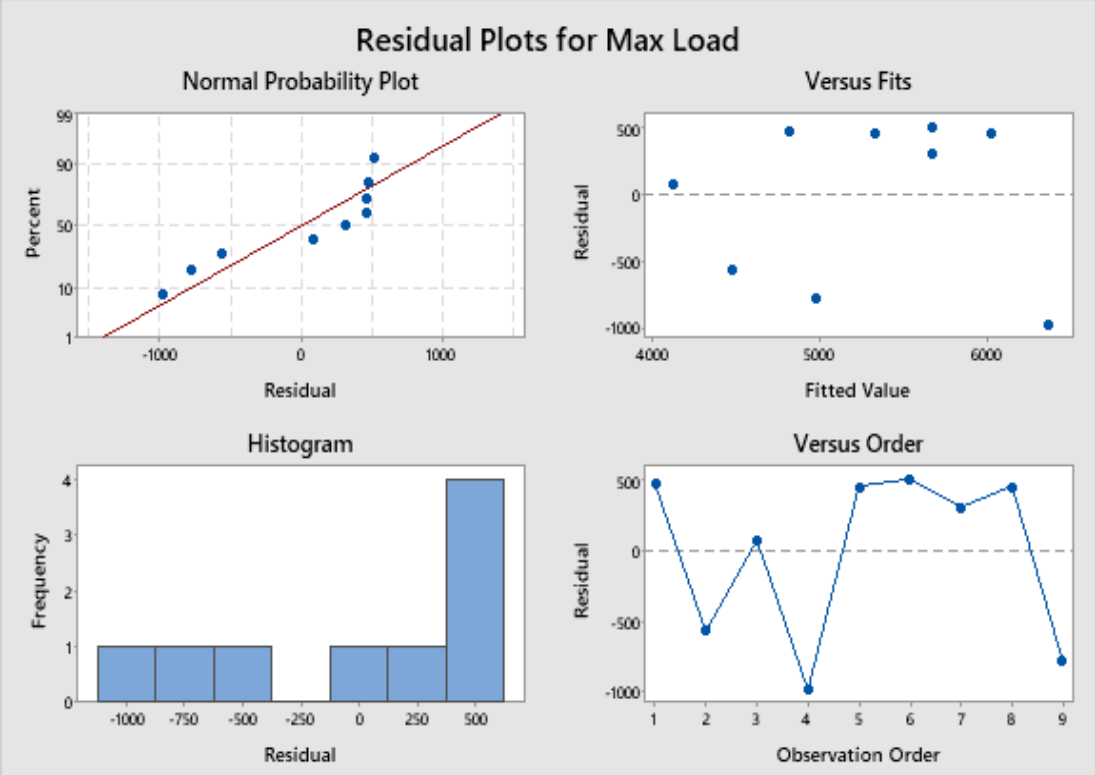
Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Regression	3	4430556	60.07%	4430556	1476852	2.51	0.173
Temperature	1	735000	9.97%	735000	735000	1.25	0.315
Time	1	1126667	15.28%	3020544	3020544	5.13	0.073
Time*Time	1	2568889	34.83%	2568889	2568889	4.36	0.091
Error	5	2945000	39.93%	2945000	589000		
Total	8	7375556	100.00%				

Regression Equation in Uncoded Units

Max Load	=	8596 – 8.75 Temperature + 497 Time – 11.33 Time*Time





COMPARING PREDICTED AND EXPERIMENTAL VALUES

Temperature	Time	Hardness (BHN)	Impact Energy (J)	Max Load	Pred_Hardness (BHN)	Pred_Impact_Energy (J)	Pred_Max_Load (N)
870	10	145	72.5	5300	143.722	103.000	5194.44
910	10	153	84	3900	142.722	89.500	4844.44
950	10	130	91	4200	140.722	75.500	4494.44
870	20	165	110	5400	162.889	78.916	5627.78
910	20	150	88	6500	160.889	65.916	5277.78
950	20	164	38	6200	159.889	51.916	4927.78
870	30	182	50	6000	181.722	54.833	6061.11
910	30	169	32	5800	179.722	41.833	5711.11
950	30	190	21	4200	178.722	27.833	5361.11

Optimization Studies

The response optimization tool is used to find at what temperature, time and quenchant combination the highest value of a particular response can be found and at which combination of all the factors can the highest value of all the responses be found simultaneously this is known as multiple response optimization. The results are as follows.

Response Optimization: Max Load, Impact Energy (J), Hardness (BHN) Parameters

Response	Goal	Lower	Target	Upper	Weight	Importance
Max Load	Maximum	3900	6500	7150	1	1
Impact Energy (J)	Maximum	21	110	121	1	1
Hardness (BHN)	Maximum	130	190	209	1	1

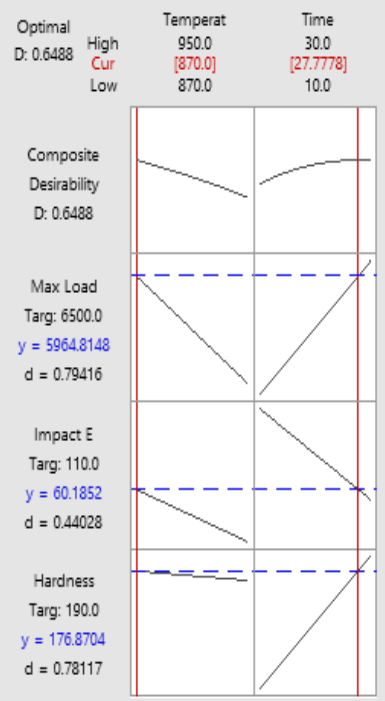
Solution

Solution	Temperature	Time	Max Load Fit	Impact Energy (J) Fit	Hardness (BHN) Fit	Composite Desirability
1	870	27.7773	5964.81	60.1852	176.870	0.648827

Multiple Response Prediction

Variable	Setting
Temperature	870
Time	27.7778

Response	Fit	SE Fit	95% CI	95% PI
Max Load	5965	590	(4521, 7408)	(3211, 8719)
Impact Energy (J)	60.2	13.8	(26.5, 93.9)	(-4.2, 124.6)
Hardness (BHN)	176.87	6.33	(161.39, 192.35)	(147.34, 206.40)



CONCLUSION

Austempering has been proven to be efficient in improving the physio-mechanical properties of mild steel, this study has shown that using locally obtained quenchants such as plantain stem extracts can be a cost-effective option. Response Surface Methodology (RSM) was used to develop models for effectively predicting the optimal time and temperature suitable for obtaining desirable properties during the austempering process. This is important because austempered mild steel has a wide range of applications and use across different industries and the development of this models we act as a guide to producing material that is suitable for specific needs. Using the optimal austempering time and temperature for achieving specific mechanical properties suitable for a particular application can save cost of production by reducing energy cost. It will also eliminate guess work in the austempering process and serve as a guide.

RECOMMENDATIONS

The models developed in this work should be used as a guide by local metal workers in making the best material that meets their needs. The scope of this work can be further extended to include more process variables, increase the range of the current variables, test for more properties and include cost analysis of the process in determining the best solution for each use case.

REFERENCES

Golanski,Shrestha, Alsagali, Charit, Potirniche, and Glazogj, "Effect of Heat Treatment on Microstructure and Hardness of Grade 91 Steel" 2015

Abioye, Atanda, Abioye, Afolalu and Dirisu "Microstructural Characterization and Some Mechanical Behaviour of Low Manganese AustemperedFerritic Ductile Iron" 2017

Dalwatkar, Prabhu and Singh"Effect of Austempering Temperature and Time on Mechanical Properties of SAE 9260 Steel"(2018)

Rusz, Schindler, Kawulok, Kawulok, Opěla, Kliber and Solowski "Transformation Kinetics of Selected Steel Grades After Plastic Deformation" (2016)

Nunes, Silva, Renzetti and Brito, "Analysis of Quenching Parameters in AISI 4340 Steel by Using Design of Experiments"(2018)

Bilal, Yaqoob, Zahid, Tanveer, Wadood, and Ahmed, "Effect of AustemperingConditions on The Microstructure and Mechanical Properties of AISI 4340 and AISI 4140 Steels" (2019)

Okwonna, Nwankwojike, and Abam "Microstrucural Investigation and Network Analysis for Austempering Process Using a Blend of Palm Kernel Oil and Bitumen on High Carbon Steel and Ductile Iron" 2017

Khuri, AI, Cornell, JA. "Response Surfaces. 2nd ed" 1996

Fedorov V. "Theory of Optimal Experiments" 1992

Khuri AI. "A measure of rotatability for response surface designs. Technometrics" 1988

BoxGEP, Draper NR. "Robust Designs" 1975, 62:347–352.

Kiefer J, Wolfowitz J, Can J Math "The equivalence of two extremum problems." 1960, 12:363

Pazman A, Dordrecht, Holland, Reidel,"Foundations of Optimum Experimental Design."1986.

Box GEP, Hunter WG, Hunter JS. "Statistics for Experimenters." New York: John Wiley & Sons

Ratkoe BL, Hedayat A, Federer WT "Factorial Designs" New York: John Wiley & Sons; 1981.

Montgomery DC, "Design and Analysis of Experiments" 6th ed. New York: John Wiley & Sons;

Box GEP "Multi-factor Designs of First Order" Biometrika 1952, 39:49–57.

McLean RA, Anderson VL,"Applied Factorial and Fractional Designs" New York: Dekker; 1984.

Box GEP, Wilson KB,J R Stat Soc."On The Experimental Attainment of Optimum Conditions" Ser 1951, 13:1–45

Box GEP, Behnken DW, Some New Three-Level Designs for The Study of Quantitative VariablesTechnometrics 1960, 2:455–475.

Box GEP, Draper NR. "Response Surfaces, Mixtures, and Ridge Analyses. 2nd ed." Hoboken,New Jersey: John Wiley & Sons; 2007.

Myers RH, Montgomery DC. "Response Surface Methodology" New York: John Wiley &SonsHoke AT.