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ORIGINAL RESEARCH ARTICLE

MODEL FOR PREDICTION OF SOME MECHANICAL PROPERTIES OF DUCTILE CAST IRON AUSTEMPERED IN JATROPHA CURCAS SEED OIL

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ABSTRACT

Austempering heat treatment is a proven way of obtaining the desired microstructure for improved mechanical properties. It is an isothermal heat treatment process in which an attractive combination of mechanical properties of austempered ductile iron (ADI) may be produced. In this paper, a statistical model for the determination of some mechanical properties was developed. The ductile cast iron was annealed after which it was austennitized at 850 and 950 °C. After the austenitizing process, it was then austempered in hot jatropha seed oil. The developed prediction model was then utilized to assess the tensile strength and hardness of the ADI. The result of the austempering process showed appreciable improvement in tensile and hardness values measured. Optimum values of tensile and hardness were 962 kN/mm^2 and 405 BHN respectively. Values of 961.4N/mm^2 and 340.1BHN were obtained using the developed model. It can therefore be concluded that, the closeness in the values obtained from the experimental measurement and the prediction model is an indication of the effectiveness of the developed model.

1.0 Introduction

Improvements in properties of metals can be achieved by controlling composition and by further processing in mechanical working and heat treatment. The heat treatment principle governs the procedures required to obtain particular microstructure in a given metal to achieve these properties to suit desirable working conditions (Aachary and Venugopalan, 2000). The importance of heat treatment lies in its ability to control a metal's structure-sensitive properties. Austempering heat treatment is a proven way of obtaining the desired microstructure for improved mechanical properties such as increased strength, toughness, wear resistance, hardness and fatigue strength in ductile iron components (Adewuyi and Afonja, 2002). It is an isothermal heat treatment process in which, depending on the applied austempering conditions, an attractive combination of mechanical properties of austempered ductile iron may be produced (Alp et al., 2005). In many applications, this renders the austempered ductile iron a valuable and an economical substitute for high strength steels (ASM, 1996). The important microstructural features of austempered ductile iron are the morphology of the ferrite, the volume fraction of retained austenite, the carbon content in retained austenite, and the presence or absence of carbide in austenite or ferrite. A mixture of bainitic ferrite retained austenite, and graphite nodules, are the most desirable combination of phases in the cast iron. Thus, the mechanical properties of austempered ductile iron may be related to three microstructural variables: bainite morphology, austenite volume fraction and the formation of martensite (ASM, 1996). Austempered ductile iron components, competes favorably with steel forgings, especially for heavy-duty parts where reliability is paramount. It is used to upgrade from standard ductile irons, and as a substitute for manganese steel and nickel-hard materials. AID is particularly cost-effective when strength is required: tensile and yield values are twice those of standard ductile iron; fatigue strength is 50 % higher. Austempered ductile iron can replace aluminum with its high strength-to-weight ratio when reduced section sizes are the requirement. ADI castings are increasingly displacing steel forgings and castings, welded fabrications and carburized steel, due to superior performance. Because of its equivalent strength, nearly 80 % of all cast and forged steels can be replaced with some grade of ADI (Ayman and Megahead, 2008). An ADI component will be 10 % lighter than steel for a given shape. ADI is three times stronger than the best cast or forged aluminum and weighs only 2.5 times as much. Because it is twice as stiff, an adequately designed ADI part can replace aluminum at a weight saving. ADI's dynamic properties exceed those of forged, cast and micro-alloyed steels. Unlike aluminum, ADI's endurance limit remains nearly constant after tens of millions of cycles. The presence of graphite in the ADI matrix improves noise damping, for quieter and smoother running components. ADI's abrasion resistance exceeds that of conventionally processed steels and irons at a lower 'bulk' hardness level. Unlike carburized steel, which loses wear resistance as the carburized layer is removed, ADI improves in service. Wear resistance is superior to steel at any hardness level, making it ideal for earth moving and high abrasion applications (Metals Handbook, 1981).

Austempering is mainly carried out in a nitrate/nitrite salt bath, due to its advantages compared to other hot baths like lead, mineral oils and polymer solutions. However, in recent years attention has been given to vegetable oils by many researchers. A study on quenching properties of sunflower, coconut oil, palm, and groundnut oils by (Canale et al., 2005) compared the quench severities obtained with petroleum oil. They reported that vegetable oils performed better than mineral oils in a decreasing order: Sunflower oil > Coconut oil > Palm oil > Groundnut oil. Sani (2008) investigated the potentials of using hot shear butter and groundnut oils as austempering quenchants for steels and cast iron. His findings indicated that these oils could be used to austemper medium carbon steel and ductile iron. A recent study by Isah (2011) evaluated Kahaya Senegalensis (Mahogany) seed oil as quenching medium in austempering of ductile iron. He reported that the Kahaya Senegalensis seed oil is an effective austempering quenchant for ductile iron. These breakthroughs could eliminate the need for a molten salt bath which has its attendant side effects such as high energy consumption, increased capital equipment cost, and the hazards the workers are exposed to when using molten salt bath.

Jatropha *curcas* seed oil was utilized as austempering medium in this research work. A prediction model was then designed to predict some of the mechanical properties of the austempered cast iron produced from the austempering process.

2.0 Materials and Methods:

2.1 Materials

The raw materials used for this investigation were high-purity sorrel pig iron obtained from Metallurgical research institute Jos, and ferroalloys of magnesium, silicon, manganese and cast iron to produce ductile iron.

2.2 Equipment

The equipment used in casting and production of test samples and mechanical tests include a 250kg rotary furnace at Nasir foundries, Jos; Nobertherm electric furnace, electric oven, Lathe, Milling machine, Pensky Martens Flash point tester and Wolpet Impact testing machine were accessed at the laboratories of the Mechanical Engineering Department, Nigerian Defence Academy, Kaduna. Metal Analyzer at the research and development laboratories of Defence Industries Corporation of Nigeria (DICON) Kaduna was also used in analyzing some of the metallic materials. *Jatropha* oil used for austempering was produced at NARIT Zaria.

2.3 Methods

2.3.1 Production of ductile iron samples

Charges consisted of 50 kg pig iron with composition C=4.17%, Si=1.66%, Mn=0.19%, S=0.01%) and a nodularizing alloy. The 25mm diameter nodularizing alloy had chemical composition (Si=45.5%, Mg= 5.85% Ca=1.08%,). A sandwich treatment technique was used. The ferrosilicon alloy was placed on a pocked in the bottom of an open heated ladle and covered with scrap in this technique. The melt was poured on the other side of the ladle to react with the magnesium alloy effectively. The melt was then cast into 'Y' blocks. The pouring temperature was 1380 °C (Metals Hand Book, 1992). The ductile iron produced had the chemical composition: C = 3.42%, Si = 3.1%, Mn = 0.21%, Cr = 0.02%, P = 0.11% and Ni = 0.00004%

2.4. Production of *Jatropha* seed oil

Dry *jatropha* seeds were collected from Rafin Sewa Gora village of Zango LGA, Kaduna state. The seeds were manually shelled and dried inside the house to prevent exposure to direct sun rays. They were then taken to National Research Institute for Chemical Technology (NARICT) Zaria, Nigeria for oil extraction. The Cold Pressed method was employed to extract oil from the seeds. The mechanically extracted jatropha oil was used in its crude form for austempering ductile iron without further processing. The chemical composition of the jatropha seed oil produced is as follows: flash point = 8.43; Acid value = 4.22; Free fatty acid = 210; Saponification value = 62.12mgKOH; Peroxide value meg/kg = 88.15; Iodine value g/100g = 40; Viscosity at 38 ^{0}C mm^2/sec = 249 respectively. Test samples were machined from the nodular cast iron. These were subjected to annealing heat treatment after which jatropha seed oil was used for the austempering.

2.5 Mechanical properties determination.

Two methods were utilized to determine the mechanical properties of the austempered ductile cast iron; the specimens were physically subjected to mechanical testing and then the developed model. In the experimental testing, the universal testing machine was used. Each of the machined samples were fixed in-between the two jaws of the machine and subjected to tensile loading till failure. Readings of extension and load where taken ~~in~~ at intervals.

2.6 Development of the Prediction Model

As described earlier in this study, the ductile iron structures where enhanced by austenitizing and austempering at selected temperature levels and times. Data was collected from the ductile iron smaples by running each condition as indicated in Tables 1 and 2 to study the factors influencing the austempering process.

Table 1: Test Factors for Austempering Process of Ductile Iron.

Factors	Low Level	High Level
Austenitizing temperature (T_φ)	800 °C	950 °C
Austempering temperature (T_ϵ)	250 °C	300 °C
Austempering time (t_ϵ)	1 hr	5 hr

In this regard, statistical design and development of a mathematical model for the austempered ductile iron was carried out. A total of 8 runs were performed on the samples, factors of interest and response variables were identified, and appropriate levels for each variable were determined. A complete factorial design was used to test every combination of the factor levels. Mathematical symbols (- and +) called "coded factor levels" representing lows and highs (actual) levels were randomly used as shown in Table 2 ~~6~~ in order to set off any lurking variables (Stankova, 2015).

Table 2: Factorial Design of Austempering Process of Ductile Iron Showing the Combination of Chosen Factors

Experiment Number	Austenitizing temperature (T_φ)	Austempering temperature (T_ϵ)	Austempering time (t_ϵ)
I	-1	-1	-1
T_φ	+1	-1	-1
T_ϵ	-1	+1	1
T_φ	+1	+1	-1
t_ϵ	-1	-1	+1
$T_\epsilon\ t_\epsilon$	+1	-1	+1
$T_\varphi\ t_\epsilon$	-1	+1	+1
$T_\varphi\ T_\epsilon\ t_\epsilon$	+1	+1	+1

The response data (Tensile strength and Hardness values) from running all the combinations of the chosen factors, each at two levels, were combined. A linear mathematical model equation to predict a given response was developed. The model will be derived from the response function expressed according to Stankova (2015) as:

$$Y = \beta_0 + \beta_1 T_\varphi + \beta_2 T_\epsilon + \beta_3 T_\varphi t_\epsilon + \beta_4 t_\epsilon + \beta_5 T_\epsilon t_\epsilon + \beta_6 T_\varphi t_\epsilon + \beta_7 T_\varphi T_\epsilon t_\epsilon \quad (1)$$

Where Y = the predicted mechanical properties (Tensile Strength and Hardness)

β_0 = the intercept

β_1 to β_7 = the model coefficient for the input factor

T_φ = Austenitization temperature (Ductile iron and steel samples)

T_ϵ = Austempering temperature and

t_ϵ = Austempering time

3.0 Results and Discussion

3.1 Experimental measurements

The result of the experimental measurement for the tensile strength and hardness test are shown in Tables 3 and 4 respectively.

Table 3: Tensile Strength of the Austempered Ductile Iron

Tensile Strength (N/mm²)		
Austenitised at 950 °C		
Time(hrs)	Austempering Temperature 250 °C *Jatropha*	Austempering Tempreture 300 °C *Jatropha*
1	726	668
2	770	690
3	822	740
4	839	814
5	962	840
Austenitised at 850 °C		
1	847	683
2	931	790
3	892	764
4	840	745
5	820	730

Table 4: Hardness strength of the Austempered Ductile Iron

Hardness (BHN		
Austenitised at 950 °C		
Time (hrs)	Austempering Temperature 250 °C *Jatropha*	Austempering Tempreture 300 °C *Jatropha*
1	331	227
2	325	297
3	346	275
4	305	291
5	340	265
Austenitised at 850 °C		
1	287.6	254
2	302.1	279.5
3	291.4	264.1
4	297.8	239.5
5	288	220

3.2 Tensile Strength and Hardness

The responses measured from running all the combinations of chosen factors at two levels are shown in Table 5. The factors had impact on the responses obtained.

Table 5: Complete Matrix Including Interactions with Effects Calculated for Austempered Ductile Iron

Run No	Main Effects		Interaction Effect					Response	
	T_ϵ	T_φ	t_ϵ	$T_\varphi T_\epsilon$	$T_\epsilon t_\epsilon$	$T_\varphi t_\epsilon$	$T_\varphi T_\epsilon t_\epsilon$	TSJ	HVJ
1	-	-	+	+	-	+	-	847	287.6
2	+	-	-	-	-	+	+	683	235.4
3	-	+	-	-	+	-	+	726	331
4	+	+	-	+	-	-	-	668	297
5	-	-	+	+	-	-	+	820	288
6	+	-	+	-	+	-	-	730	220
7	-	+	+	-	-	+	-	962	340
8	+	+	+	+	+	+	+	840	265
								784.5	283
Effect $_{TSJ}$	-108.5	29	107	18.5	2.5	97	-34.5		
Effect$_{HVJ}$	-57.3	50.5	-9.5	2.8	-14.2	-2	-6.3		

Where: TSJ = Tensile strength values for samples austempered in jatropha oil.
HVJ= Hardness values for samples austempered in jatroph oil.

3.3 Discussion

The combination of low levels of austempering temperature, austenitizing temperature and time, produced austempered ductile iron of tensile strength value as high as 847 N/mm^2 for jatropha oil. A lower tensile strength values of 840 N/mm^2 for jatropha oil at the combination of high austempering temperature, high austenitizing temperature and time. The highest tensile strength values of 962 N/mm^2 were achieved at a combination of low austempering temperature with high austenitizing temperature and time. It means a low level of austempering temperature would increase tensile strength. The developed mathematical model equation for the prediction of the tensile strength values with the fitted factors of temperatures and time in coded form for jatropha seed oil is expressed as:

$$T.S = 784.5 + 14.5T_\varphi - 54T_\epsilon + 9.3T_\varphi T_\epsilon + 53.5\, t_\epsilon + 1.3T_\epsilon t_\epsilon + 48.5\, T_\varphi t_\epsilon - 17T_\varphi T_\epsilon t_\epsilon \quad (2)$$

where: T_φ = Austenitizing temperature (Ductile iron samples)
T_ϵ = Austempering temperature and
t_ϵ = Austempering time in all the equations.

The value for the intercept of 784.5 represents the average of all the tensile strength values obtained after 8 runs of the test (actual responses). By substituting the values of the main and interactions effects in coded form in Equation (1) for any experimental condition using jatropha seed oil as austempering medium, the tensile strength values for the austempering process of ductile iron were calculated. The predicted values for tensile strength were determined by putting the code factor levels into the coded model in Equation (2).

The effect of T_ϵ, t_ϵ and $T_\varphi T_\epsilon$ caused bigger effect on the predicted tensile strength values than other effects. These are in the magnitude of -108.5, 107 and 97 for samples austempered. The comparison of actual and predicted tensile strength of the ADI is presented in Table 6.

Table 6: Actual and the Predicted Tensile Strength Values

	Tensile Strength Values (N/mm^2) of ADI Jatropha Seed Oil Quenchant	
Run No	Actual	Predicted
R1	847	849.5
R2	683	683.4
R3	726	726
R4	668	668
R5	820	820
R6	730	730
R7	962	961.4
R8	840	840.6

Table 6 compares the predicted values of tensile strength values with the responses obtained under different experimental conditions. The predicted values are very close to the actual values obtained from the experiment utilizing jatropha. The reliability of the model equations predicted well with the studied austempered ductile iron. Responses have been ascertained within the selected temperatures and time.

3.4 Prediction of the hardness of austempered ductile iron

A similar statistical design and mathematical model were developed to predict the hardness of the ductile iron austempered in jatropha oil. The responses obtained for hardness values depended on austenitization temperature, austempering temperature and time. Combining a low level of austempering temperature with high austenitizing temperature and austempering time produced the highest hardness of 405BHN for the samples austempered in jatropha seed oil. High levels of austempering temperature and time and low levels of austenitizing temperature produced the most negligible hardness value of 220 BHN. This suggests that high a level of austempering temperature and low levels of austenitizing temperature contribute greatly to the decrease in hardness value. The developed mathematical model equation for the prediction of hardness value (HV) with the fitted factors of temperature and time in coded form for samples austempered in jatropha seed oil can be expressed as:

$$H.V = 283 + 25.3T_{\varphi} - 28.7T_{\epsilon} + 1.4T_{\varphi}T_{\epsilon} - 4.8\, t_{\epsilon} - 7.1T_{\epsilon}t_{\epsilon} - T_{\varphi}t_{\epsilon} - 3.2T_{\varphi}T_{\epsilon}t_{\epsilon} \quad (3)$$

Table 7 presents the predicted hardness values compared with the actual values of responses obtained under different experimental conditions. The predicted values obtained by applying Equation (3) are found to be very close to the actual values obtained.

Table 7: Actual and Predicted Hardness Values of ADI at different conditions

	Hardness Values (BHN) of ADI Jatropha Seed Oil Quenchant	
Run No	Actual	Predicted
R1	287	287.7
R2	235.4	235.3
R3	331	331.1
R4	297	297.1
R5	288	287.9
R6	220	219.9
R7	340	340.1
R8	265	264.9

4. Conclusions

From the results and analysis of the results obtained, the following conclusions could be drawn.

(i) Jatropha, seed oil was able to cause the formation of 'ausferrite' and 'bainite' structures at 250°C in the ductile cast iron specimens.

(ii) There was an appreciable improvement in the mechanical properties of ductile iron when austempered in jatropha seed oil. The as-cast tensile strength, yield strength and hardness values of 560 N/mm^2; 266 BHN which increased to optimum values of 1039N/mm^2 and 405 BHN for samples austempered in the jatropha seed oil.

(iii) The developed statistical model for predicting the tensile and hardness values for the austempered ductile iron compared well with the values obtained using the experimental method of determining mechanical properties.

References

Aachary, J. and Venugopalan, D. 2000 Microstructural Development and Austempering Kinetics of Ductile Iron during Thermomechanical Processing. Metallurgical and Materials Transaction, 31(A): 2575- 2585.

Adewuyi, BO. and Afonja, AA. 2002. Austempered Ductile Iron, a Viable to Steel. Nigerian Journal of Engineering and Management, 1(1): 6-13.

Alp, T. Wazzan, AA. and Yilmaz, F. 2005. Microstructure Property Relationships in Cast Irons. The Arabian Journal for Science and Engineering, 2 (B): 163-175.

American Society Metals (ASM) 1996. Specialty hand book, cast iron. 1st edition, (Davis, JR. (ed.)). ASM international, Ohio, pp. 356-392.

Ayman, H. and Megahed, MM. 2008. Fracture toughness characterization of austempered ductile iron produced using both conventional austempering processes. Materials and Design, 3: 1866-1877.

Canale, LCF., Fernandes, MR., Agustinho, SCM., Totten, GE. And Farah, AF. 2005. Oxidation of Vegetable Oils and its Impact on Quenching Performance. International Journal of Materials and Product Technology, 24(1-4): 101-125.

Isah, LA. 2011. Evaluation of Khaya Senegalensis (Mahogany) Seed Oil as Quenching Medium in Austempering Process of Ductile Iron. Ph.D thesis. Department of Metallurgical and Materials Engineering, Ahmadu Bello University, Zaria, Nigeria.

Metals Handbook, 1992. Heat Treating of Ductile Irons. 9th Edition, Ohio, American Society of Metals Metal Park, USA., 15: 358-488.

Sani, S. 2008. Potentials of using some Vegetable Oils as Quenchants for Austempering of steel and Cast Irons. Ph.D thesis. Department of Metallurgical and Materials Engineering, Ahmadu Bell University, Zaria, Nigeria.

Stankova, K. 2015. Probability and Statistics for Engineers and Scientists. Prentice Hall India Ltd India.