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Effect of Austempering Process Parameters on the Mechanical Properties of Ductile Cast Iron Quenched In Moringa Seed Oil

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Abstract
The use of Austempered Ductile Iron (ADI) is rapidly gaining ground because of its excellent properties such as high strength, high wear and abrasion resistance, excellent fatigue, high toughness and high strength-to-weight ratio, that are suitable for most of engineering applications. However, determination of the right process parameters needed to developADI products with combination of desirable properties that are most appropriate for specific application is a major challenge that faces production and material design engineers. There is need to ensure that ADI materials are either over-or under- processed to guarantee the development of the candidate material required for an engineering application. Hence, the effects of austempering process parameters on the mechanical properties of austempered ductile cast iron were studied. Ductile cast iron was developed by alloying cast with 0.06% magnesium. The cast samples were machined and then austenized at 950^{0}C, held at this temperature for 1 hour before quenching in moringa seed oil. Thereafter, the samples weresubjected to isothermal treatment at different austempering temperatures of 240^{0}C, 350^{0}C and 420^{0}C for different time durations of 2.5, 3.5 and 4 hours. The samples of the austempered ductile cast iron were examined for microstructural details and then subjected to tensile testing, hardness and percentage elongation. The results obtained within the time range of 2.5 – 4 hours for the various temperatures of 240^{0}C, 350^{0}C, 420^{0}C indicate that the values of tensile strength, hardness and percentage elongation were within the ranges of 1151 – 849MPa, 306 – 267BHN and 2.86 – 5.97% respectively. It was found that austempering temperature range of 350 - 420^{0}C yielded increase in percentage elongation with decrease in tensile strength and hardness. This is due to the presence of coarser ausferrite matrix with higher amount of carbon diffusion. However, lower temperature austempering process such as 250^{0}C showed improved tensile strength and hardness with low ductility. This shows that optimum tensile strength value of ADI is obtainable at low austempering temperature while maximum elongation requires higher austempering temperature. It was therefore concluded that at specificaustempering temperature, the mechanical properties of austempered ductile cast iron could vary with time and temperature. Thus, there is a strong correlation between specific engineering properties of austempered cast iron and the austempering parameters.

Keywords: *Tensile strength, cast iron, quenching, ductility, hardness, austempering.*

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I. Introduction:

Cast iron is an alloy of iron and carbon with the percentage composition of carbon ranging between 2.0 – 6.67%. It is most suitably processed by casting method. Hence, it is referred as cast iron. Most of the cast iron products commercially produced have high carbon content which increases brittleness and consequently reduces ductility and strength properties. This gave birth to the development of an improved grade of cast iron known as ductile iron. This grade of cast iron has the graphite present in form of spheroids[1].

Ductile cast iron was developed by maintaining low content of sulfur, and phosphorus in the alloy coupled with ladle addition of 0.03 – 0.06% of a modifier or nucleating agents such as magnesium or cerium to the liquid metal.The presence of the alloying element causes the graphite to precipitate in all directions as spheroidal nodules during solidification. The mechanical properties of spheroidal graphite iron are superior to that of flaky graphite in grey cast iron. This is caused by the morphology of the graphite. In the former, the graphite spheroids are dispersed in the matrix which obstructs dislocation movement and thus produces a good influence on the mechanical properties. However, in the later, the graphite has pointed ends that act as stress raisers that are detrimental to the mechanical properties[1,2]**.**

Since the discovery of ductile iron, its use is gaining ground in engineering applications continuously. This is traced to its excellent mechanical properties. Hence, most research interests on ductile iron began to focus on the development of better properties of the same alloy. This led to the immergence of austempered ductile iron which was formed by isothermal treatment of the ductile iron[3].

Austempering is a heat treatment process adopted to achieve the full potential of ductile cast iron. It has been used to achieve much higher ranges of strength and elongation in heat treatment process. Austempered ductile iron is known for its high strength and ability to perform very well under different wear conditions, rolling contact, fatigue, and abrasion. Hence, it has replaced forged steel in many engineering applications [4].

Ductile cast iron undergoes remarkable transformation when subjected to a special isothermal treatment process. The microstructure obtained is known as ausferrite which consists of fine acicular ferrite with carbon enriched stabilized austentite[2]. It is this constituent phase that yieldsthe microstructure with combination of excellent properties that are superior to other ferrous and nonferrous engineering alloys. The processing and development of austempered cast iron involves heating of ductile cast iron in a heat treatment furnace to austenitizing temperature of 850^0C – 950^0C. The austenitized castings are held at the austenitizing temperature to dissolve carbon in austenite. The precise temperature depends on the grade of austempered ductile cast iron intended to produce. This is followed by rapid cooling through quenching in a quenching medium and subsequent isothermal treatment maintained within temperature range of 235 - 425^0C. The quenching time is controlled within few seconds, which do not allow the formation of pearlite that would adversely affect the mechanical properties. The samples are held at austempering temperature for some time for isothermal transformation of ausferrite. The quenching temperature is maintained within the specified range to stay above the point of martensitic formation [5].

In the conventional ductile cast iron, ferrite produces lower strength and hardness but higher ductility and toughness. However, in austempered ductile cast iron, extremely fine grained acicular ferrite provides an exceptional combination of high strength with good ductility and toughness. The stabilized austenite improves toughness and ductility and response to surface treatment. This produces material that is twice as strong as pearlitic ductile iron but still retains high elongation and toughness.The combination gives rise to superior wear resistance and fatigue strength [6]**.**

The properties of austempered ductile cast iron product such as hardness, tensile strength, and elongation depend on the processing parameters and the microstructure of the material. Increase in austempering temperature yields decrease in hardness and strength with increase in elongation and impact toughness. This is traced to coarse microstructure and the increase in the amount of stabilized austentite due to diffusion of carbon at elevated temperature[7].

The development of austempered ductile cast iron has offered design engineers opportunity to use a new class of ferrous materials with exceptional mechanical properties and relative low production cost. Hence, it was established that austempered ductile cast iron is a good alternative in many applications where steel and aluminum were previously used [6]. The potentials of this material have been exploited by manufacturers to produce light weight and high performance machine components used in miscellaneousand heavy duty industrial applications[8].

It is necessary to have good and consistent control of time and temperature during austempering process. This will ensure that the desired structure and properties of austempered ductile iron is achieved. The austentizing time and temperature are controlled to ensure formation of fine grain austenite and uniform carbon content in the matrix. However, the exact temperature depends on the desired grade. The quenching time must be restricted within few seconds. This avoids the formation of undesirable phases which may impair the mechanical properties [9]. Therefore, this suggests that correct austempering process parameters should be properly selected while processing ADI to ensure that the material is neither over nor under processed. This will guarantee the development of the candidate materials for specific applications.

In view of this research need, this study sought to investigate the effects of austempering process parameters, i.e. temperature and time, on the properties of ADI material. The results obtained will be a useful tool for industrial quality control standards.

II. Materials And Methods

2.1 Materials

The materials used for this study include cast iron, magnesium, and moringa seed oil.The equipment suchas copula furnace, heat treatment furnace, lathe machine, grinding and drilling machine, universal tensile testing machine, Brinell hardness testing machine and metallurgical microscope were used both in the production and in the tests. The casting process of the ductile iron, with the heat treatment processes alongside with mechanical property tests were carried out at the foundry workshop in Scientific Equipment Development Institute (SEDI) Enugu Nigeria. The microstructural examinations were carried out at the Metallurgical

Laboratory of Federal University of Technology, Owerri. Imo State Nigeria. The chemical composition of the as-cast ductile cast iron is as shown in Table 1.

Table 1: Chemical composition of ductile cast iron

Fe	C	Si	Ni	Mn	Mg	Cr	P	Cu
Balance	3.2	1.7	1.0	0.25	0.07	0.07	0.03	0.1

2.2 Methods

The methods that were adopted for this study were categorized into three stages which are casting and alloying, heat treatment, testing of the properties with microstructural examination inclusive.

2.2.1 Casting and Sample Preparation

100kg of cast iron was melted using the cupola furnace. The melt was tapped into the mold meant for the specimen samples. 0.06%of magnesium as the alloying element was used as ladle addition. This was done to ensure that the magnesium is retained in the melt at such high temperature.The alloy metal was poured into the mold cavity and allowed to cool to room temperature in air. Subsequent to the casting stage, the different test samples of the ductile iron were cut, ground, polished and machined to the dimensions specified for various tests.

2.2.2 Heating Treatment

Twenty-seven (27) test samples were subjected to an austempering heat-treatment process. Each of the samples was austenitized at 950^{0}C for 1 hour in the furnace. The austenitizing time of one hour was chosen to ensure complete austenite is formed before quenching in moringa seed oil [2]**.**The samples were then maintained at different temperatures of 240^{0}C, 350^{0}C and 420^{0}C for time durations of 2.5, 3.5 and 4 hours to ensure good formation of ausferrite structure. The choice of these temperatures was based on the temperature limitsabove and below which other phases such as pearlite and martensite could form. The design of the experiment was framed in a way to study the effect of the austempering temperature and time on the mechanical properties of the samples.

2.2.3 Determination of Mechanical Properties

The test samples were subjected to tests to determine tensile strength, percentage elongation and hardness values. The methods which were used wereas contained in [2].

Tensile Test

A universal tensile testing machine was used to perform the tensile test. The sample specimen of standard shape with a dimension of 14 and 50mm for gauge diameter and gauge length respectively was used. The dimensions of grip diameter and grip length were determined as 20 and 70mm respectively. The specimen was subjected to tensile load until fracture occurred under room temperature. The tensile strength and percentage elongation were calculated using the formulae:

$$\text{Tensile Strength} = \frac{\text{Maximum load (N)}}{\text{Original cross-sectional area (mm}^2)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.1)$$

$$\text{Percentage elongation} = \frac{\text{Elongation at fracture } (L_f - L_0)}{\text{Original guage length } L_0} \quad \ldots\ldots\ldots\ldots\ldots\ldots(2.2)$$

Where L_f is length at fracture and L_o is original length.

Hardness Test

Brinell hardness testing machine with a 20mm diameter steel ball indenter was used to determine this property. A load of 3000kg was applied for a period of 15 seconds. The hardened steel ball penetrated the specimen and the diameter of the indentation was measured. The Brinell hardness number was calculated as shown in [2]. It was computed as the value of the load divided by the surface area of the indentation. which is mathematically represented as;

$$\text{Hardness } H_B = \frac{2P}{\pi D[D - \sqrt{D^2 - d^2}]} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.3)$$

Where P is the applied load (kg), D is the diameter of the indenter and d is the diameter of the indentation (mm).

2.2.4 Micro Structural Examination

Standard test techniques were used to conduct the microstructural examination of the specimens using metallurgical microscope. The samples were ground roughly using abrasives of 320 and 400 grits while fine grinding was done using abrasive of 600 grits. Rough polishing was done with powdered diamond dust abrasive of 6 microns' size and further polishing with emerald cloth on a rotating polishing wheel. The specimen was etched using 2% nital solution for few seconds [7]. The samples were viewed under metallurgical microscope. The images of the micrographs were captured at magnification of 100 times.

III. Results And Discussion

3.1 RESULTS

The mechanical properties obtained for both ductile cast iron and austempered ductile iron samples are shown in Table 2. The microstructural analysis resultsof the samples are presented in plate 1 – 4.

Table 2: Mechanical Properties of the Non-Heat Treated (Control) and Austempered Samples

Austempering Temperature (^{0}C)	Time (hr)	Tensile Strength (MPa)	Hardness (BHN)	Elongation (%)
Ductile Cast Iron (Control sample)	-	732	184	7.41
240	2.5	1151	306	2.86
	3.5	1032	281	2.95
	4.0	995	273	2.95
350	2.5	1050	283	3.58
	3.5	932	280	3.67
	4.0	914	268	3.32
420	2.5	898	280	5.04
	3.5	855	275	5.73
	4.0	849	267	5.97

Plate 1: Micrograph of sample ductile iron (control)

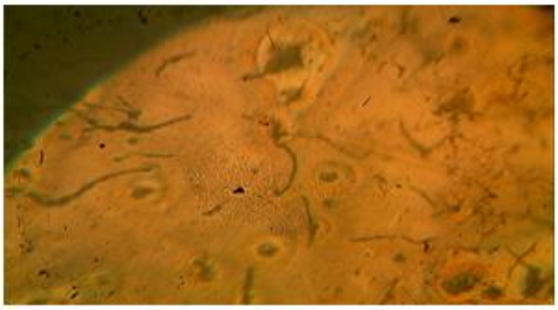

Plate 2: Micrograph of sample austempered at 240^{0}C

Plate 3:Micrograph of sample austempered at 350^{0}C

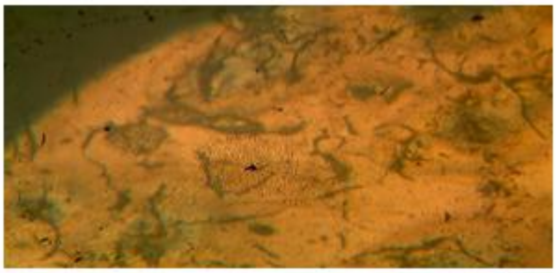

Plate 4: Micrograph of sample austempered at 420^{0}C

3.2 DISCUSSION

It is obvious from Table 2 that the tensile strength and hardness of ductile cast iron were lower than those of austempered ductile iron. According to [7, 10 and 11], ductile cast iron contains more ferrite leading to higher ductility and lower strength and hardness.

3.2.1 Effect of the Austempering Process Parameter on Tensile Strength

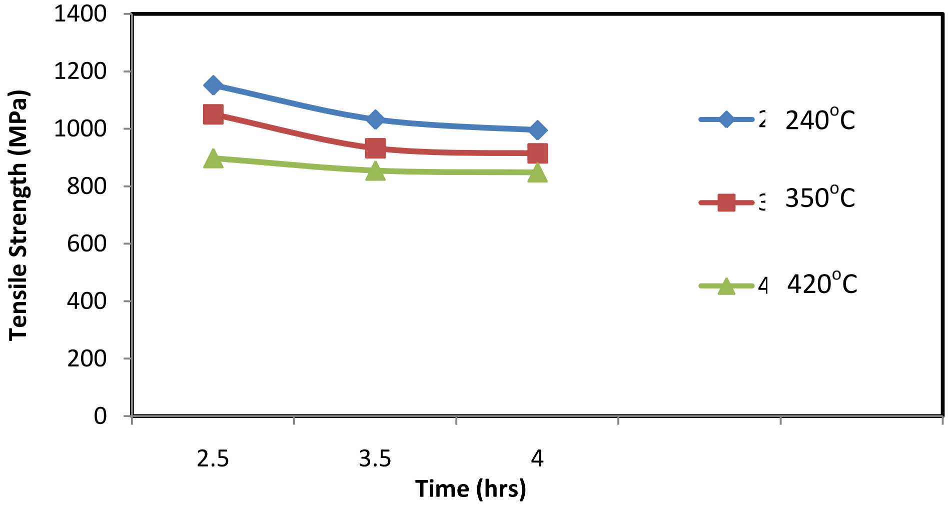

Fig. 3.1: Effect of autempering temperature and time on tensile strength of ADI material

The effect of varied austempering temperature and time on tensile strength of ADI material is shown in Figure 3.1. It was observed that at the austemperingtemperature of 240^0C, tensile strength decreased from 1151 – 995 MPa when the austempering time increased from 2.5 – 4.0 hours. Further increase in temperature to 350^0Cyielded a range of value of 1050 - 932 MPa within the same corresponding time durations. When the austempering temperature finally increased to 420^0C, the tensile strength value reduced further to a range of 989 – 849 MPa in the same trend.

This shows that at definite temperature value, tensile strength progressively decreased with increase inaustemperingtime. However, comparison of the effect of various temperature levels on same property shows that tensile strength of ADI decreases with increase in austemperingtemperature. At low temperature, coarser bainitic ferrite with higher retained austenite and graphite nodules were developed leading to inhibition of crack propagation which yielded high ductility and good fatigue. This is in line with the postulation of [11]. Hence, for a high value of tensile strength, lower values of austempering temperature will be preferred. This is due the needle shaped bainitic ferrite microstructure which develops at low austempering temperatures that improves the strength property.

3.2.2 Effect of the AustemperingProcess Parameter on Percentage Elongation

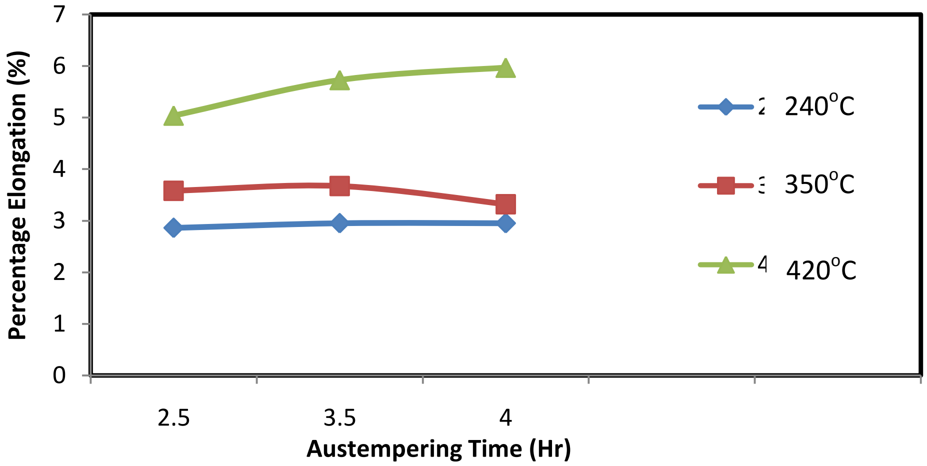

Fig. 3.2: Effect of sutempering temperature and time on the percentage elongation of ADI material

Figure 3.2 shows the effect of austempering temperature and time on the percentage elongation of ADI material. From the results, it was found that percentage elongation generally increased with increase in austempering temperature and time. It has been reported that at elevated temperature, more carbon stabilized austenite is formed, which results in increased ductility[7].The increase in ductility is traceable to the coarse bainitic ferrite and carbon diffusion in the structure. According to [7 and 11], "the nodule shaped bainitic ferrite decreases the stress concentration thereby preventing propagation of cracks in the material leading to high ductility". However, it was noted that at the temperature of 240^{0}C, constant elongation value was maintained constant between 3.5 – 4.0 hours while at the austempering temperature of 350^{0}C, the elongation value slightly decreased from 3.67 to 3.32% between 3.5 and 4.0 hours.

3.2.2 Effect of the Austempering Process Parameter on Hardness

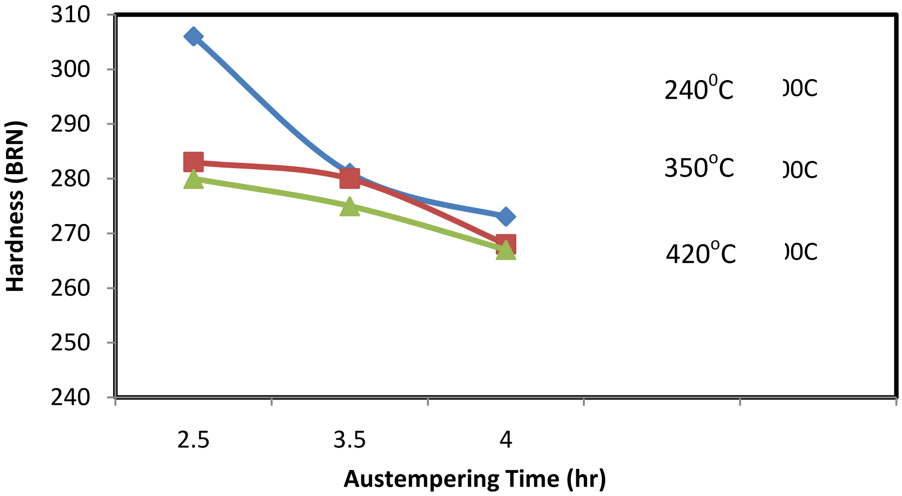

Fig. 3.3: Effect of austempering temperature and time on the hardness of ADI material

The results obtained in hardness test of the ADI materialare presented in Figure 3.3. This indicates that the hardness values yielded at the lower austempering temperature range of 240 - 350^{0}C maintained a steady progressive decrease from 306 – 268BRN with respect to time. When the temperature level was elevated to 420^{0}C, hardness value decreased further to 267BRN. It was also noted that the hardness value was decreasing with temperature and time.

From the overview of the general results obtained, it is observed that austempering temperature is one of the major factors that determined the mechanical properties of the ADI castings. The influence of austempering time was found to be dependent on the austempering temperature.

In most of the temperature values considered, it was found that with increase in austempering time, tensile strength and hardness decreased while percentage elongation showed increase. It was also noted that the combination of lower tensile strength and hardness values with higher percentage elongation values were achieved at higher austempering temperature range of 350 - 420^{0}C. This is traced to the coarse ausferrite matrix with more amount of carbon diffusion as reported in literatures. [7].On the other hand, the lower austempering temperature of 240^{0}C yielded a combination of highvalues of tensile strength and hardness with low value of percentage elongation.

It was therefore established from the results that when austempering temperature is chosen, appropriate austempering timeduration is necessary to optimize the properties of ADI material through the formation of a stable structure of austenite. When the time is too short, there will be insufficient diffusion of carbon to the austenite to stabilize it. Hence, a martensitic structure will be formed when it is cooled to room temperature [3]. The resultant microstructure will indicate high hardness value with low ductility which correlates with results obtained. This may not be desirable for most load bearing applications. In contrast, excessive austempering time will result to decomposition of ausferrite into ferrite and carbide. This in turn yields low strength.

3.2.3 Microstructure

The structure of the ductile iron is presented in plate 1. The microstructure consists of pealite, ferrite with graphite in small spherical shape. The nodular shape graphites dispersed in the matrix act as a barrier to dislocation movement. This in turns improves the mechanical properties of the material.The microstructure of the samples austempered at various temperatures are shown in Plates 2 – 4. The ausferrite structures obtained in the material consist of acicular ferrite matrix and layers of carbon enriched austenite. The samples austempered at higher temperatures such plates 3 and 4 were observed to have coarser ausferrite matrix with higher amount of carbon stabilized austentite**.** The acicular ferrite phase is shown as dark needle like structure while the orange white regions show the carbon enriched austentite[7, 10].

IV. Conclusion

Based on the findings made in this study, the following conclusion were drawn:
At a specific austempering temperature, the mechanical properties of austempered ductile cast iron vary with time. Thus, there is a strong correlation between specific engineering properties of austempered cast iron and the austempering parameters.
Austempering at temperature range of 350 - 420^{0}C yields increase in percentage elongation with decrease in hardness and tensile strength. However, lower temperature austempering process such as 250^{0}C indicated improved tensile strength and hardness with low ductility
Prolonged austempering time duration above 3.5 hours is not appropriate for most engineering properties of austempering ductile cast iron.
Optimum tensile strength values of ADI is obtainable at low austempering temperature while maximum elongation requires higher austempering temperature.
Austempering process can improve to a great extent, all the mechanical properties of the ductile cast iron which were investigated.

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