A STUDY OF HEAT TREATMENT EFFECTS ON NODULAR IRON

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ABSTRACT

In their bid to produce cast iron latter than Malleable Iron, the scientist discovered the ductile iron or S.G. Iron (spherodial Graphite iron) way back in 1948.The use of this type of cast iron as an engineering material has been increasing day by day ever since its discovery. It is now replacing steel in many important engineering applications. The production of S.G Iron increased to a large extent during last two decades. The excellent combination of mechanical properties obtained in S.G. iron can further be informed by the heat treatment. The most recent development in this regard is the production of Austempered Ductile Iron (ADI).It provides an excellent combination of high tensile strength, wear resistance along with good corrosion resistance and quite significant amount of ductility. Due to these factors, S.G. or ductile iron are austempered when a very favourable combination of various properties is required. But this type of treatment is bit tricky, since it require controlled heating and isothermal holding of the material.

Keywords – nodular cast iron, heat treatment, austempering

1. Introduction:

Ductile Iron also referred to as **"**Nodular Iron" or Spheroidal graphite iron was patented in 1948.After a decade of intensive development work in the 1950's, ductile iron had a phenomenal increase in the use as an engineering material during the 1960's, and the rapid increase in commercial application continues today.

An unusual combination of properties is obtained in ductile iron because the graphite occurs as spheroids rather than as graphite flakes as in grey iron. This mode of solidification is obtained by adding a very small, but specific amount of Mg & Ce or both to molten iron of proper composition. The base iron is severely restricted in the allowable contents of certain minor elements that can interfere with graphite spheroid formation. The added Mg reacts with S or O in the melt or molten iron and the way the graphite is formed. Control procedures have been developed to make the processing of ductile iron dependable.

The high C & Si content of ductile iron provide the casting process advantageous, but the graphite nodules have only the nominal influence on the mechanical properties of the melt. Ductile iron, like malleable iron, exhibits a linear stress- strain ratio, a considerable range of yield strengths and as its name implies, ductility. Castings are made in a wide range of sizes with sections which are very thin or very thick.

The different grades are produced by controlling the matrix structure around the graphite either the as cast or by subsequent heat treatment. Only minor compositional differences exist among the regular grades, and these adjustments are made to promote the desired matrix microstructures. Alloy addition may be made to abet in controlling the matrix structure as- cast to provide response to heat treatment. Special analysis ductile iron and high alloy ductile irons provide unusual properties for special application.

1.1 Birth of Ductile Iron

In spite of the progress achieved during the first half of 20th century in the development of Gray and malleable Irons, foundry men continued to search for the ideal cast iron – an as cast "gray iron" with mechanical properties equal to superior to Malleable Iron. J.W. Bolten speaking at the 1943 convention of the American Foundry men's Society (AFS), made the following statement. "Your indulengence is requested to permit the posing of one question. Will real control of graphite shape be realized gray iron? Visualization a material, processing (as cast) graphite flakes or grouping resembling those of malleable iron instead of elongated flakes."

A few weeks later, in the International Nickel Company Research Laboratory, Keith Dwight Millis made a ladle addition of magnesium (as a copper-magnesium alloy) to cast iron and justified Bolton's optimism- the solidified castings contained no flakes, but nerely perfect spheres of graphite. Ductile iron was born! At the time of Morrogh's presentation, the International Nickel Company revealed their development, starting with Millis' discovery in 1943, of magnesium as a graphite spherodizer. On October 25, 1949, patent 2,486,760 was granted to the International Nickel Company, assigned to Kieth D. Millis, Albert P. Gegnebin and Norman B. Pilling. This was the official birth of Ductile Iron, the beginning of 40 years of continual growth worldwide, in spite of recessions and changes in materials technology and usage.

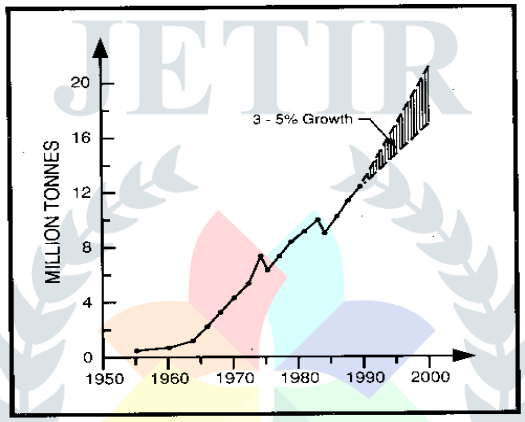


Fig 1.1 worldwide growth of ductile iron

1.2 Various grade of S.G. irons accepted as per international norms are given below:

International standard ISO 1083: 1987

Grade	Tensile Strength (N/mm^2)	0.2 % Proof Strength (N/mm^2)	Elongation (%)
900-2	900	600	2
800-2	800	480	2
700-2	700	420	2
600-3	600	370	3
500-7	500	320	7

450-10	450	310	10
400-15	400	250	15
400-18	400	250	18
400-18L	400	250	18
350-22	350	220	22
350-22L	350	220	22

1.3 Chemical Composition:

Chemically this material is same as gray iron and is Fe-C-Si alloy. It led to the development of cast iron technology since 1948. As the name suggests, it was developed to overcome the brittle nature of gray and white irons. It is quite ductile in as-cast form and negates the need for long heat treatments such as those required to produce malleable iron.

1.4 Microstructure:



Fig 1.2 Microstructure of gray and ductile iron

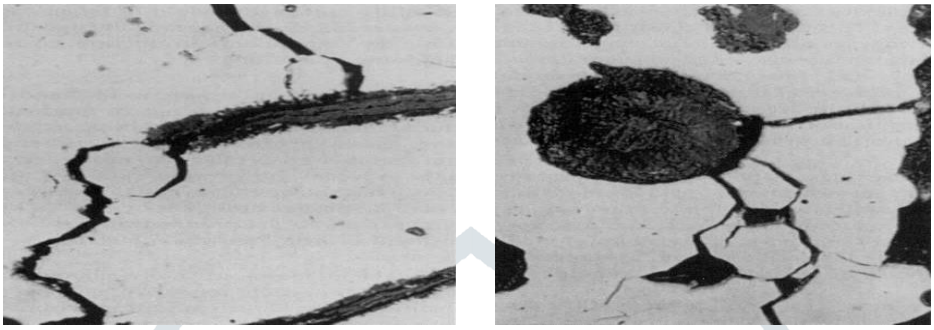
Engineering applications of cast iron have been traditionally based upon gray (Flake graphite) irons providing a range of tensile strengths between about 150 N/mm^2 and 400 N/mm^2 with recommended design stresses in tensile applications of 0.25 x tensile strength. Despite their limited strength gray irons provided very useful l combinations of properties, which have ensured there wide continuing use. In fact gray irons still account for nearly 70 % of all iron castings produced. In contrast ductile irons have tensile strengths ranging from 350 to 1500 N/mm^2 with good elongation and high toughness. They now account for about 25 % of iron casting production serving in safety critical applications where they have replaced steel casting, forging and fabrications with technical and cost advantage.

The main difference between ductile iron and gray iron is the morphology of graphite particles as shown in figure 1.2 which take on a nodular or almost spherical form after suitable treatments are made to the melt. The major micro structural constituents of ductile iron are: the chemical and morphological forms taken by carbon, and the continuous metal matrix in which the carbon and/or carbides are dispersed.

The following important micro structural components are found in ductile iron.

1.4.1 Graphite

This is the stable form of pure carbon in cast iron. Its important physical properties are low density, low hardness and high thermal conductivity and lubricity. Graphite shape, which can range from flake to spherical, plays a significant role in determining the mechanical properties of cast irons. Figures 1.3 (a) and (b) show that graphite flakes act like cracks in the iron matrix, while graphite spheroids act like "crack arresters", giving the respective irons dramatically different mechanical properties.



(a) (b)

Fig 1.3: graphite nodules as a crack arrester.

1.4.2 Carbide:

Carbide, or cementite, is an extremely hard, brittle compound of carbon with either iron or strong carbide forming elements, such as chromium, vanadium or molybdenum. Massive carbides increase the wear resistance of cast iron, but make it brittle and very difficult to machine. Dispersed carbides in either lamellar or spherical forms play in important role in providing strength and wear resistance in as-cast pearlitic and heat-treated irons.

1.4.3 Ferrite:

This is the purest iron phase in a cast iron. In conventional Ductile Iron ferrite produces lower strength and hardness, but high ductility and toughness. In Austempered Ductile Iron (ADI), extremely fine-grained acicular ferrite provides an exceptional combination of high strength with good ductility and toughness.

1.4.4 Bainite:

Bainite is a mixture of ferrite and carbide, which is produced by alloying or heat treatment.

1.4.5 Pearlite:

Pearlite, produced by a eutectoid reaction, is an intimate mixture of lamellar cementite in a matrix of ferrite. A common constituent of cast irons; pearlite provides a combination of higher strength and with a corresponding reduction in ductility which meets the requirements of many engineering applications.

1.4.6 Martensite:

Martensite is a supersaturated solid solution of carbon in iron produced by rapid cooling. In the austempered condition it is very hard and brittle. Martensite is normally "tempered" - heat treated to reduce its carbon by the precipitation of carbides - to provide a controlled combination of high strength and wear resistance.

1.4.7Austenite:

Normally, a high temperature phase consisting of carbon dissolved in iron, it can exist at room temperature in austenitic and austempered cast irons. In austenitic irons, austenite is stabilized by nickel in the range 18-36%. In austempered irons, austenite is produced by a combination of rapid cooling which suppresses the formation of pearlite and the super saturation of carbon during austempering, which depresses the start of the austenite to-martensite transformation far below room temperature. In austenitic irons, the austenite matrix provides ductility and toughness at all temperatures, corrosion resistance and good high temperature proper-ties, especially under thermal cycling conditions. In austempered Ductile Iron stabilized austenite, in volume fractions up to 40% in lower strength grades, improves toughness and ductility and response to surface treatments such as fillet rolling.

1.5 Family of Ductile Irons:

With a high percentage of graphite nodules present in the structure, mechanical properties are determined by the Ductile Iron matrix. The importance of matrix in controlling mechanical properties is emphasized by the use of matrix names to designate the following types of Ductile Iron.

1.5.1Austenitic Ductile Iron:

Alloyed to produce an austenitic matrix, this Ductile Iron offers good corrosion and oxidation resistance, good magnetic properties, and good strength and dimensional stability at elevated temperatures.

1.5.2 Ferritic Ductile Iron:

Graphite spheroids in a matrix of ferrite provide an iron with good ductility and resistance and with a tensile and yield strength equivalent to a low carbon steel. Ferritic Ductile Iron can be produced "as-cast" but may be given an annealing heat treatment to assure maximum ductility and low temperature toughness.

1.5.3 Ferritic Pearlitic Ductile Iron:

These are the most common grade of Ductile Iron and are normally produced in the "as cast" condition. The graphite spheroids are in a matrix containing both ferrite and pearlite. Properties are intermediate between ferritic and pearlitic grades, with good machinability and low production costs.

1.5.4 Pearlitic Ductile Iron:

Graphite spheroids in a matrix of pearlite result in an iron with high strength, good wear resistance, and moderate ductility and impact resistance. Machinability is also superior to steels of comparable physical properties. The preceding three types of Ductile Iron are the most common and are usually used in the as-cast condition, but Ductile

Iron can be also be alloyed and/or heat treated to provide the following grades for a wide variety of additional applications.

1.5.5 Martensitic Ductile Iron:

Using sufficient alloy additions to prevent pearlite formation, and a quench-and-temper heat treatment produces this type of Ductile Iron. The resultant tempered martensite matrix develops very high strength and wear resistance but with lower levels of ductility and toughness.

1.5.6 Bainitic Ductile Iron:

This grade can be obtained through alloying and/or by heat treatment to produce a hard, wear resistant material.

1.5.7Austempered Ductile Iron (ADI):

ADI, the most recent addition to the Ductile Iron family, is a sub-group of Ductile Irons produced by giving conventional Ductile Iron a special austempering heat treatment. Nearly twice as strong as pearlitic Ductile Iron, ADI still retains high elongation and toughness. This combination provides a material with superior wear resistance and fatigue strength.

1.6 Objective of work:

The objective of this work is to determine the mechanical properties and microstructure of heat treated ductile iron with two different grades. One is with Cu and other is without Cu. After that compare these properties with different treatment conditions, the treatment conditions are mainly tempering at different temperature and austempering at constant temperature and variation of time. Mechanical properties are:

1. Tensile strength (U.T.S., 0.2% elongation),
2. % Elongation,

Then these mechanical properties are related with microstructure and fracture surfaces of the different samples after treatment.

2 Literature Review

Ali M.Rashidi and M.Moshrefi-Torbati [1998] have investigated the effect of tempering conditions on the mechanical properties of ductile iron with dual matrix structure. Tempering is the most important heat treatment process that was applied to quenched steel & cast iron. The objectives of this process include reducing the brittleness of the material, improvement of toughness & ductility and also reducing the probability of cracking. The composition of the material analyzed was (in Wt. %) 3.56% C, 1.94% Si, 1.33%Ni, 0.28 %Mn, 0.29% Mo, 0.017%P, 0.012%S. In order to obtain a complete ferrite structure, the sample were first heat treated at 950˚C for 2 hrs. The samples were tempered at 300˚C, 400˚C, 450˚C, 500˚C, 600˚C for 1 hrs. And also at 500˚C for 30, 90,120, 150& 180 min. Finally, the samples were machined down to standard dimension and then tension experiment was carried out. It was seen that by increasing the tempering temperature, there was a rise in elongation percentage, prior to the sudden jump that occurred within the range of 400-500 ˚C, followed by a slow & gradual increase. Therefore, if the aim is to achieve

high toughness & ductility, the dual phase ductile iron with ferrite-martensite matrix structure should be tempered at temperature higher than 500˚C.Again as the tempering temperature increased, the yield strength ultimate tensile strength initially decreased then within the range of 400-500˚C remained roughly constant and then there was a rise in elongation percentage for tempering up to 120 min before it is finally dropped. The reason for this reduction was likely to be due to a phenomena called temper embitterment. Within the temperature range of 400-500˚C, both strength and yield stress decrease .Longer duration of tempering period at 500˚C increases the elongation percentage for tempering period up to 120 min reduces strength and yield stress, thereafter, they both go up again. For any combination of temperature of tempering and tempering period and of up to 120 min. the amount of ultimate tensile strength can satisfactorily be obtained from the master curve's strength-tempering parameter.

3 EXPERIMENTAL PROCEDURE

3.1 Raw Materials

Ductile iron produced in a commercial foundry known as L&T kansbahal, has been used for this experiments. Two grades of ductile iron were used. The differences between these two grades were: one contains copper, while other was without copper. They were designated as Grade A and Grade B. Chemical compositions of raw material obtained by weight chemical analysis method used in this study are given in Table 3.1.

Table 3.1chemical composition of raw material obtained by weight

All are in wt %	C	Si	Mn	Cr	Ni	Mg	Cu	S	P
Grade A	3.55	2.1	0.18	0.03	0.12	0.038	0.41	0.009	0.024
Grade B	3.57	2.22	0.23	0.03	0.42	0.045	……	0.011	0.026

3.2 Test Specimen Preparation:

For different tests the solid block of ductile iron was cut to thickness of 4-6 mm using power hacksaw. Then they are grinded, polished and machined to the dimension required for various experiments to be carried out.

3.3 Heat Treatment:

Twenty samples from each grade were taken in a group. To homogenize the samples kept them in a muffle furnace for one hour at 927ºC, some samples were conventionally treated and some were austempered for different times with constant temperature.

3.3.1 Annealing and Normalizing:

After austenization for annealing samples were cooled in furnace for 12hrs and normalizing was done by rapid cooling of samples in still air for 30 minutes.

3.3.2 Quenching and Tempering:

After austenization some samples were quenched in oil for 20 mins. Apart from two or three samples rest were tempered at 200°C, 400°C and 600°C for 1 hrs.

3.3.3 Austempering:

For austempering, the samples were heated at 925°C for 1 h for austenization and then transferred quickly to a salt bath (salt combination was 50 wt. % NaNO3 and 50 wt. % KNO3) maintained at

260°C. The samples were kept in the salt bath for different times as 30 mins, 1 hr., 1.5 hr., and 2 hr. After which they were allowed to cool in still air. The isothermal austempering cycle used in this study is shown in figure.

3.4 Hardness Measurement:

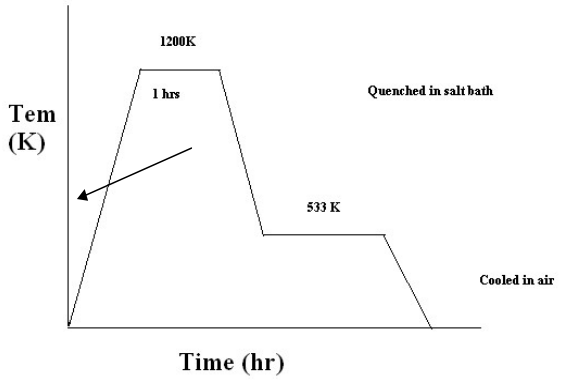


Fig 3.1: Isothermal cycle for austempering treatment

The heat treated samples of dimension 8×8×3 mm were polished in emery papers(or Si C papers) of different grades for hardness measurement. Rockwell Hardness test was performed at room temperature to measure the macro hardness of the ductile iron specimens in a scale. The load was applied through the square shaped diamond indenter for few seconds during testing of all the treated and untreated samples. Four measurements for each sample were taken covering the whole surface of the specimen and averaged to get final hardness results. A load of 60 kg was applied to the specimen for 30 seconds. Then the depth of indentation was automatically recorded on a dial gauge in terms of arbitrary hardness numbers. Then these values were converted to in terms of required hardness numbers (as Brielle's or Vickers hardness numbers).

3.5 Tensile Testing:

Tensile test were carried out according to ASTM (A 370-2002). Specimens of "Dog Bone Shape" shown in figure 3.2 were prepared for tensile test, which were machined to 5mm gauge diameter and 30 mm gauge length. Test were conducted by using Instron 1195 universal testing machine connected to computer to draw the stress–strain curves and recording the tensile strength, 0.2 proof stress and elongation. Test were performed at room temperature (298K) with strain rate of 9×10^{-3} up to fracture. The tensile load of 50 KN was applied to the specimen up to the breaking point.

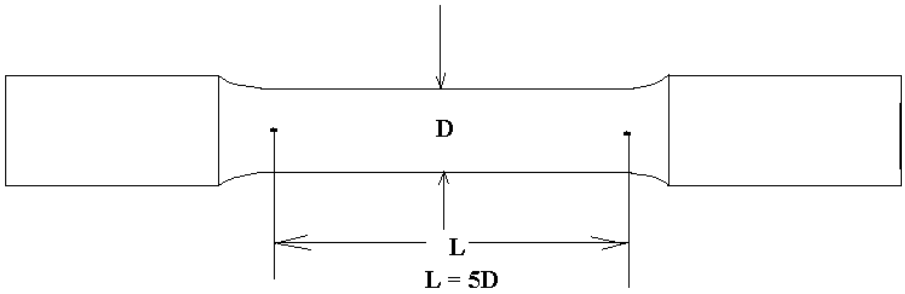


Fig 3.2: Specimen used for tensile properties

Advanced materials are used in a wide variety of environments and at different temperature and pressure. It is necessary to know the elastic and plastic behavior of these materials under such conditions. Such properties as tensile strength, creep strength, fatigue strength, fracture strength, fracture toughness, and hardness characterize that behavior. These properties can be measured by mechanical tests. The picture of tensile testing machine used in our laboratory is Instron 119.

3.6 Optical Investigation:

3.6.1 Micro-structural observations:

Before and after heat treatment, the samples were prepared for micro structural analysis. From each specimen a slice of 4 mm is cut to determine the microstructure. These slices are firstly mounted by using Bakelite powder then polished in Si C paper of different grades (or emery papers) then in 1 µm cloth coated with diamond paste. The samples were etched using 2% nital (2% conc. Nitric acid in methanol solution). Then the microstructures were taken for different heat treated specimen by using Scanning Electron Microscopy (SEM).

3.6.2 Fractoraography:

Fracture surface or surface morphology of the samples which fractures in different manners (ductile, Brittle and mixed mode fracture) after tensile test for treated and untreated condition are analyzed by using Scanning Electron microscopy (SEM). For this samples were cleaned with Acetone to remove any dust or impurity on the surface of specimens before SEM.

4 RESULT AND DISCUSSION

4.1 Mechanical Properties:

The mechanical properties measured by using Instron1195and dimensions of specimen was carried out according to ASTM (A 370-2002), are given in Table 4.1 (a),(b) and 4.2(a),(b) lists the mechanical properties viz. Tensile strength, 0.2% Proof stress, % Elongation, Hardness etc. Of cast irons (with and without Cu addition) respectively.

Table 4.1(a): Mechanical properties of treated ductile iron with Copper

Treatment	U.T.S (MPa)	0.2% Y.S.(MPa)	% Elongation	Hardness(RA)

Annealed	369.8	183.9	18.08	47
Normalized	406	156	5.19	58
Oil quench	419	172.9	2.89	76
Temp 21	399	215.9	6.9	71
Temp 41	338	205	10.08	65
Temp61	308.8	192	12.8	65

Table 4.1 (b): Mechanical properties of treated ductile iron without Copper

Treatment	U.T.S(MPa)	0.2% Y.S(MPa)	% Elongation	Hardness(RA)
Annealed	240.8	203.9	18.12	43
Normalized	462	219	7.92	72
Oil quench	348.9	238.9	4.09	76
Tem21	321	208	8.17	70
Tem41	282	194	14.32	62
Tem61	243	167	15.4	56

*U.T.S. - Ultimate Tensile Strength,

*Y.S. – Yield Strength

*Temp21,41,61-tempered at 200°C,400°C, 600°C for 1 hrs.

Table 4.2 (a): Mechanical Properties of austempered ductile iron with Copper.

Treatment	U.T.S(MPa)	Y.S.(MPa)	% Elongation	Hardness(RA)
Austempered	872.9	152	21	72

0.5				
Austempered 1.0	967	168.9	12.82	71
Austempered 1.5	745	161.9	16.74	66
Austempered 2.0	713	145.8	9.07	62

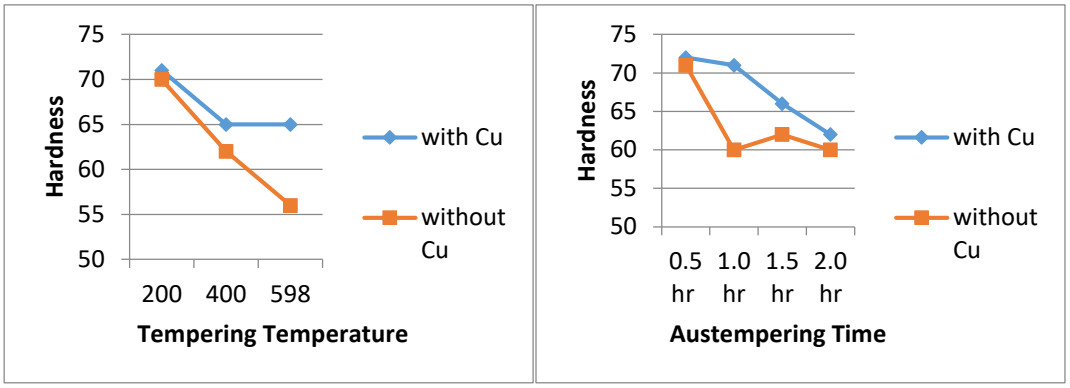
*The subscript in austempered denotes the time of austempering.

Table 4.2 (b): Mechanical Properties of austempered ductile iron without Copper.

Treatment	U.T.S(MPa)	Y.S.(MPa)	% Elongation	Hardness(RA)
Austempered 0.5	850	175	33	71
Austempered 1.0	942	192	13	60
Austempered 1.5	732	195	22	62
Austempered 2.0	685	138	19	60

4.1.1 Hardness measurement:

Figure 4.1.1 (a) and (b) shows the variation of hardness values in (Rockwell Hardness 'A' scale) with the treatment conditions. The Fig. 4.1(a) shows that hardness decreases as the tempering temperature increases in both cases (with Cu and without Cu additions). This is due to the transformation of martensite to tempered martensite. The hardness of martensite is due to the tetragonal structure of the martensite where carbon occupies tetrahedral voids. This structure results from the diffusion less transformation which occurs by shear mechanism. So when martensite is tempered, diffusion of C from the tetrahedral sites of the BCT structure takes place and thus the tetragonality of martensite gets reduced. Alternatively, the structure of martensite becomes less strained after holding it at a higher temperature but less than the lower critical temperature because of carbon diffusion. Thus, the hardness of tempered martensite is lesser than quenched martensite.



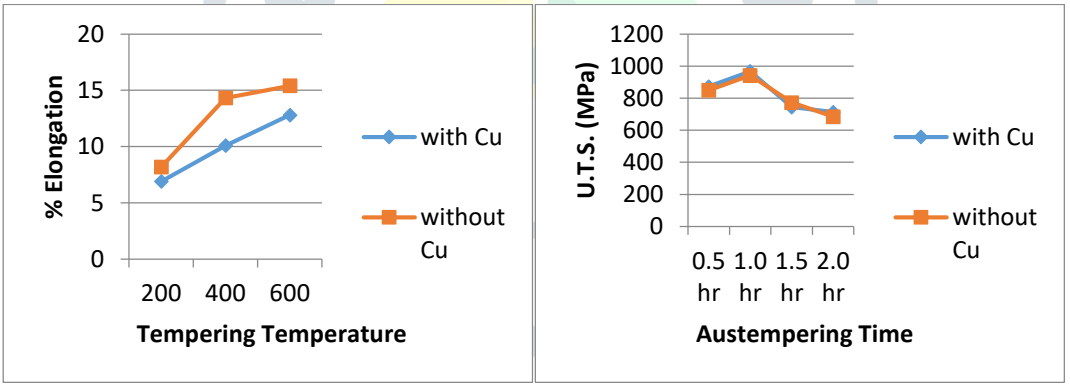
(a) (b)

Fig 4.1.1: Variation of hardness with tempering temperature and austempering time.

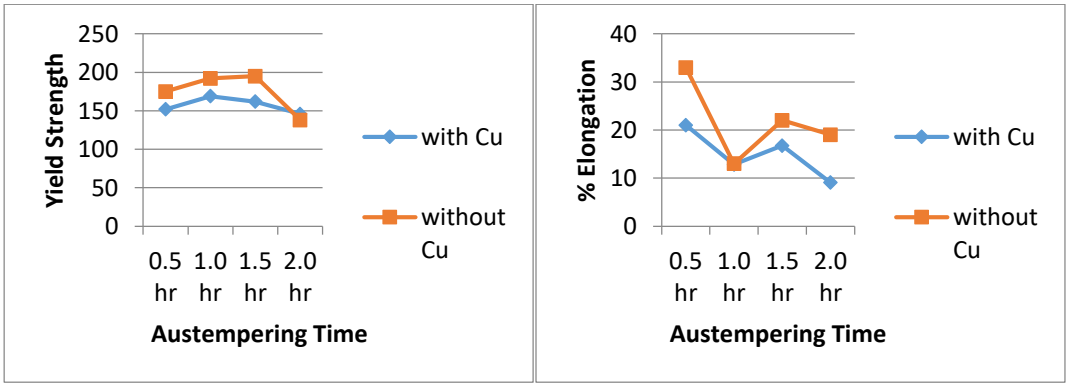
For austempered samples the variation of hardness is shown in figure 4.1 (b). Hardness of plain ADI is slightly lower than the Cu enriched ADI, and hardness reduces proportionally with increase in austempering time. This decrease in hardness is due to the disappearance of martensite phase. Lower austempering time yield a finer structure and therefore higher hardness was obtained. But as the holding/treatment time increased further, the hardness values were again decreased due to the occurrence of coarse plate-type structure (of bainitic) matrix phase.

4.1.2 Tensile Strength and Elongation:

The variation of U.T.S., 0.2 % proof stress and elongation with temperature in the case of tempering, and with time for austempered samples, of two different grades are shown in figure 4.1.2 (a), (b), (c) and (d).



(a) (b)



(c) (d)

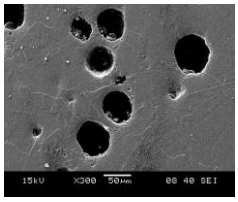
Fig 4.1.2: Mechanical properties with different treatment conditions

Comparing the tensile strength of two different grades of samples with different treatments, it is observed that, there is a slight change in their properties. The U.T.S of normalized samples was greater than the annealed samples but less than the tempered and austempered samples. The tensile properties vary with the matrix type, i.e. - pearlitic (in case of normalized samples), martensitic (in case of quenching and tempering) and bainitic (in case of austempered samples) matrix. So 0.2% proof stress and U.T.S increases but elongation decreases depending on pearlite content of the matrix. Tempered samples have higher tensile properties than the normalized samples, but as the tempering temperature is increased there was a decrease in U.T.S and 0.2% Y.S, as shown in fig 4.1.1(a) and (b). The elongation of tempered samples is less than annealed sample but higher than normalized samples, because of the formation of martensite and tempered martensite etc. On the other hand, the ductility (% elongation) increases with the tempering temperature as shown in figure 4.1.2 (c).

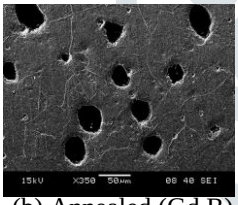
By austempering treatment, the variation of mechanical properties depends on the change in the nature and amount of transformation/formation of bainite phase. At lower austempering times, the U.T.S., 0.2% proof stress and elongation increases initially, then decreases and with further increase in treatment time attains a steady state, as shown in fig 4.1.2 (f). But with longer austempering times, the value of U.T.S., 0.2% proof stress decreases. The decrease in elongation while austempered for an intermediate time range may be due insufficient unreacted low carbon austenite. But as the time increases further, the retained austenite reduces, and ductility again increases with time. The increase in strength initially at low time interval is due to the high amount of martensite derived from the unreacted austenite, but as the time increases above 30 minutes the first stage reaction commences in the intercellular regions for which strength decreases and ductility increases further to a maximum value; that indicates the tolerable amount of martensite. The sample alloyed with copper has increased ductility and lesser strength than that of the sample without copper content.

4.2 Optical investigations:

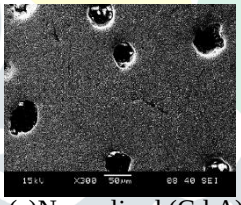
4.2.1 Microstructures:



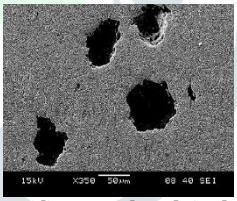
(a) Annealed (GDA)



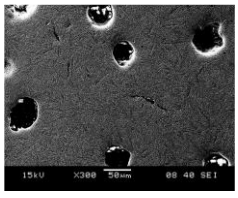
(b) Annealed (Gd B)



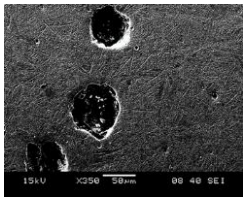
(c)Normalised (Gd A)



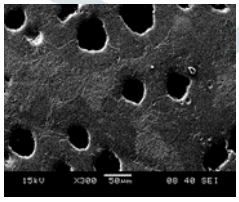
(d)Normalised (Gd B)



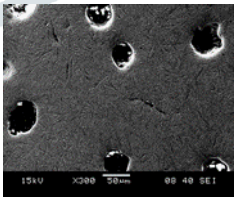
(e)Tempere2(GdA)



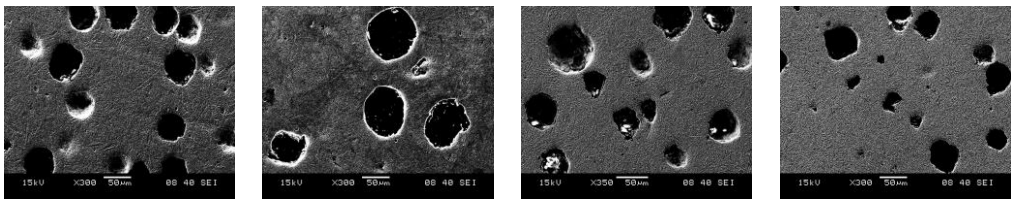
(f) Tempered2 (Gd B)



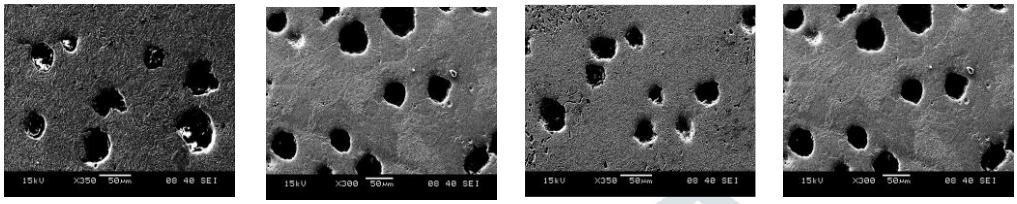
(g) Tempered 4(Gd A)



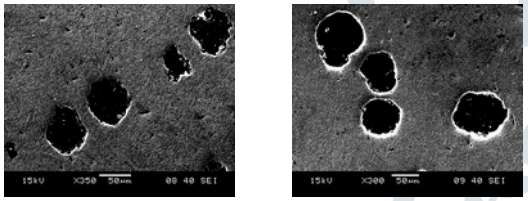
(h) Tempered 4 (Gd B)



(I)Tempered 6 (Gd A) (j) Tempered6 (Gd B) (k) Austempered0.5 (Gd A) (l) Austempered0.5 (GdB)



(m) Austempered 1(Gd A) (n) Austempered 1(Gd B) (o) Austempered 1.5(Gd A) (p) Austempered 1.5 (Gd B)



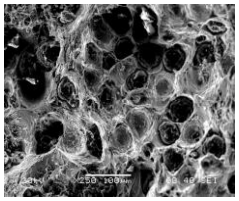
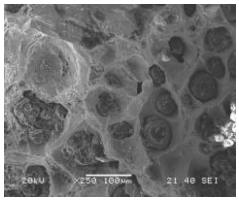
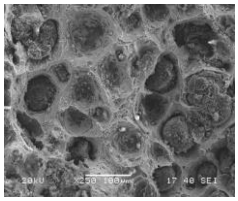
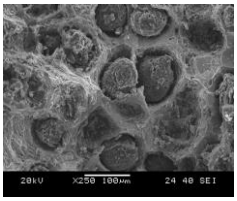
(q) Austempered 2 (Gd A) (r) Austempered 2(Gd B)

The microstructure of ductile iron in as cast condition is mostly pearlitic. After different treatments there is a change in matrix/phase structure, number of nodules and their spheroidicity. These cause changes in the mechanical properties of ductile iron. The microstructures after different types of treatments of two different grades are shown in figur4.2.1 from (a) to (r).There is although not much differences in the matrix pattern of two different grades (with Cu and without Cu) of ductile iron, but the number of nodules and nodule count in case of grade A is higher than grade B. Also there is a change in the length and sharpness of (platelet type) bainites in case of grade A is better than grade B.

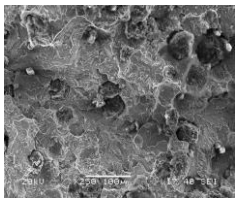
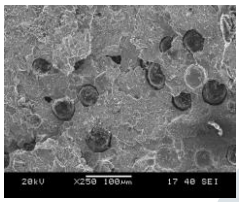
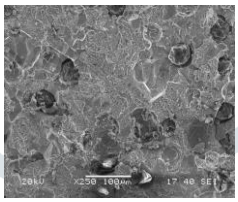
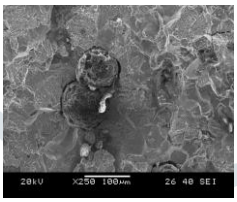
After annealing treatment, the microstructure of both the grades consist of spheroidal graphite embedded in a ferrite matrix but the number of nodules is higher in the copper enriched grade. So, both the structures show high ductility but lower values of hardness and strength. After air cooling or normalizing, the microstructures in both the cases show a typical “bull’s eye” structure in which most of the graphite nodules are surrounded by a ferritic envelope. Both the graphite nodules and ferritic envelopes are embedded in a pearlitic matrix. When quenching and tempering is done, the microstructure consists of a martensite matrix with graphite nodules. After tempering at higher temperatures, the matrix phase changes to tempered martensite, thus relieving the internal stresses and increasing the strength and ductility, compromising with hardness.

After austempering treatment, the entire matrix changes to plate-like ausferrite and/or bainitc ferrite and high carbon austenite in both the cases. Graphite nodules are embedded in the matrix, as shown in figure4.2.1 from (k) to (r).At lower austempering time, very fine needle-type or acicular bainitic ferrite are observed with small amount of retained austenite and some martensite, which increases the strength. But as the austempering time increases this fine structure with no martensite appears and increases the strength and decreases the ductility and hardness due to disappearance of martensite and with increase in bainitic ferrite .This relates the microstructure with the mechanical properties. So there is an optimum value of time and temperature of treatment to obtain a good combination of strength and properties.

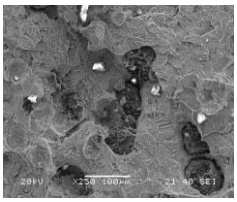
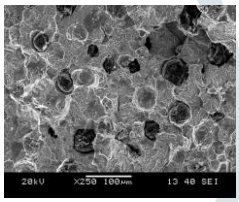
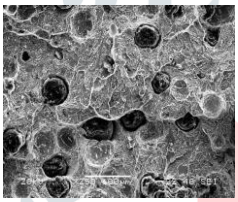
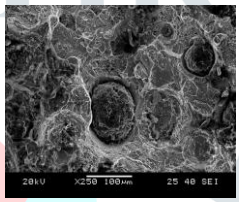
4. 2.2 Fractrography:

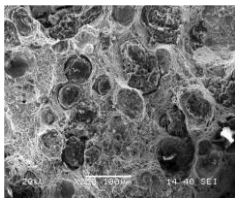
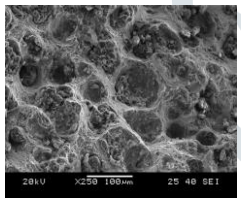
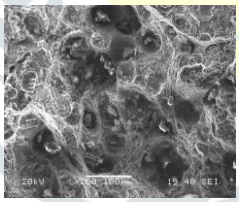
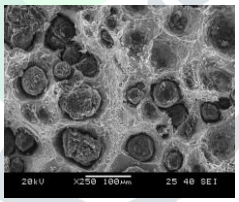
(a)As-cast (GdA) (b) As-cast (Gd B) (c) Annealed (Gd A) (d) Annealed (GdB)

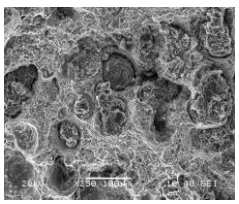
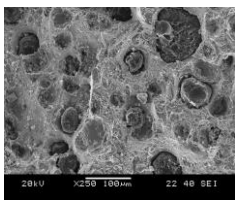
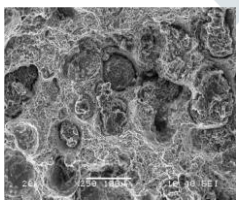
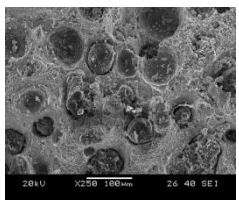
(e) Normalized (Gd A) (f) Normalized (Gd B) (g) Tempered2 (Gd A) (h) Tempered2 (Gd B)

(i) Tempered 4(Gd A) (j) Tempered 4 (Gd B) (k) Tempered6 (Gd A) (l) Tempered 6(Gd B)

(m)Austempered0.5 (Gd A) (n) Austempered 0.5(Gd B) (o) Austempered 1(Gd A) (p) Austempered 1(Gd B)

(q) Austempered 1.5 (Gd A) (r) Austempered 1.5 (Gd B) (s) Austempered 2(Gd A) (t) Austempered 2(Gd B)

The morphology of the fracture specimens are analyzed by Scanning Electron Microscopy (SEM). Figure 4.2.2 shows the fracture surface of the different samples. As cast ductile iron shows a fully dimpled fracture. The fracture pattern in annealed samples are same as in as cast ductile iron with greater numbers of dimples as shown in fig4.2.2(c)and (d) , while the fracture in normalized samples show a brittle fracture with river patterns in the vicinity of pearlitic areas as shown in fig4.2.2(e) and (f), for both the grades. So, the fracture surfaces confirms with the high ductility in annealed samples and low ductility in normalized samples. The fracture pattern of tempered samples at low temperatures show a

mixed mode of fracture because of the untransformed martensite presents at that temperature, but as the tempering temperature increases the major fracture pattern is ductile in nature. So, this conforms to the increase in ductility i.e. the elongation percentage. There is decrease in strength and hardness when tempering temperature is increased from 200°C to 400°C. But, the strength and hardness values remain constant with further increase in tempering temperature to 600°C. This is due to the occurrence of strain-hardening phenomena.

In case of austempering treatment, at lower treatment times, the fracture pattern (in both the grades) shows a mixed mode of fracture (ductile and brittle), because of the presence of retained austenite and some amount of martensite. But as austempering time is increased, the fracture bears a dimple type appearance because of the disappearance of martensite phase. But, if time is further increased, brittle fracture dominates.

5 Conclusion:

The correlation between the microstructures and mechanical properties of Ductile Iron were studied along with their fracture surfaces for two different heat treatment processes- Quenching and Tempering; and Austempering. We also studied the effect of Copper on the microstructures, mechanical properties and fracture surfaces after heat treating.

For Quenching and tempering heat treatment cycle, we observed the following:

1. As the tempering temperature increases, ductility of the samples also increased but compromising with hardness and strength.
2. The strength and hardness values were more for the sample with copper while ductility was found to be more for the sample without copper.
3. The fracture surfaces showed a mixed mode of fracture for both the grades of samples. But, the percentage of dimple fracture was found to increase with tempering temperature.
4. The microstructure in as cast condition shows the pearlitic matrix with graphite nodules in both grades of samples, while after quenching and tempering the matrix converted into the martensite and tempered martensite. Thus, the strength and elongation was increased in tempered samples, but hardness decreases.

For Austempering heat treatment cycle, we observed the following:

1. As the holding time for austempering increases, the tensile strength initially increases and then decreases. Contrary to it, % elongation first decreases and then increases with time. The hardness values normally decreases with austempering time.
2. The strength and hardness values for the sample with copper are more while ductility was found to be more for the sample without copper.
3. The fracture surfaces showed a mixed mode of fracture for shorter austempering time. The percentage of dimple fracture then increased with time. For longer austempering time, percentage of cleavage fracture was found to be more.
4. The microstructure was ausferrite or bainitic ferrite and retained austenite with graphite nodules embedded in it for all periods of time. But, the morphology of bainite was changed from needles to plate like structure as the austempering time increases. So, the Strength and hardness decreases with time and ductility.

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