Effect of processing parameters on austempering behavior of alloyed/unalloyed ductile iron

Thesis submitted in partial fulfillment of the requirements for the degree of

Master of Technology
In
Metallurgical & Materials Engineering

By

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Under the supervision of

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National Institute of Technology, Rourkela-769008

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NATIONAL INSTITUTE OF TECHNOLOGY
ROURKELA

CERTIFICATE

This is to certify that, the work embodied in this project report entitled **“Effect of processing parameters on austempering behavior of alloyed/unalloyed Ductile iron”** by Shri Lakshmana Rao Tangi is an authentic record of work carried out by him under my supervision and guidance for partial fulfillment of the requirements for the degree of Master of Technology in Metallurgical and Materials engineering; National Institute of Technology, Rourkela.

To the best of my knowledge, this work has not been submitted to any other University/Institute for the award of any degree or diploma.

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Date: 25.05.2012 **Lakshmana Rao Tangi**

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Abstract

Ever since its discovery in 1948, the use of ductile iron is increasing continuously due to the combination of its various excellent mechanical properties. Excessive amount of research is being carried out to develop even better properties. Austempererd ductile iron is the most recent development in the area of ductile iron or SG iron. Two types of spheroidal graphite (SG) cast iron samples with different weight percentage of copper were austempered at four different temperatures. The austempering temperatures were 200˚C, 300˚C, 350˚C, 400˚C.The influence of austempering process (i.e time and temperature) on the mechanical properties of spheroidal graphite iron was investigated as a function of austempering time and temperature. The cooling rate and the quenching technique adopted play an important role for the property development of spheroidal graphite iron. XRD analysis has also been carried out to study the formation different phases during isothermal transformation at different austempering conditions. Graphite morphology has been studied by SEM. The samples were taken for XRD analysis from the centre of the castings for this investigation. It was found that both the austenite (111) and ferrite (110) lines are identified nearly in all cases. The maximum intensity of the austenite (111) line is increasing with increasing temperature but ferrite (110) line is increasing with increasing austempering time and decreasing with austempering temperature. Hence austempering calls for very precise control of process variables (austempering time and temperature). It has been found from the result that ADI having the alloying element copper (grade N2) achieved significant mechanical properties as compared to other grade (N1) throughout the different austempering process adopted in this study.

Keywords: Spheroidal Graphite Iron, Austempering (temperature and time), XRD, SEM analysis

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

In recent years, there has been an appreciable importance in energy saving which has led to the development of light weight, durable and cost effective materials. For these purposes, there is a requirement to continually generate new materials and checkout those already in account. One such material is ductile iron. Research efforts on this material, have mainly, focused on possible development of mechanical properties by subjected it to appropriate heat treatment and by alloying elements.

A ductile iron which is treated to a particular isothermal heat treatment process (austempering) is known as austempered ductile iron (ADI). The properties of Austempered ductile iron is produced by the particular heat treatment, so the only requirement for austempered ductile iron is better ductile iron.

Ductile Cast Iron has a remarkable transformation when subjected to the austempering process. The obtained microstructure, known as "Ausferrite",which consist of fine acicular ferrite with carbon enriched stabilized austenite [1] and gives ADI its special attributes. The new microstructure (ADI) results with superior ability to many traditional, high performance, ferrous and aluminium alloys. Ausferrite has strength twice the strength for a given level of ductility compared to the martensitic, pearlitic, or ferritic structures formed by conventional heat treatments.

The mechanical properties of the austempered ductile iron are depending on the ausferrite microstructure. The austepmered matrix is responsible for significantly better tensile strength to ductility ratio and is more than any other grade of ductile iron [2].

An unusual combination of properties is obtained in austempered ductile iron because of the ausferrite microstructure. These properties mainly depend on the heat treatment conditions and alloyed elements. Alloy additions may be made to austempered ductile iron with a view to control the matrix structure.

The present investigation is to find out the effect of austempering process on the mechanical properties of the spheroidal graphite iron and to characterize the graphite morpgology during different austempering parameters i.e., austempering temperature and time.

CHAPTER 2

LITERATURE REVIEW

2.1 LITERATURE REVIEW

Cast irons are basically alloys of iron and carbon like steels but contain greater amount of carbon. Cast irons content is between 2 and 6.67% of carbon. High carbon content tends to make the cast iron very brittle and most commercially manufactured types are in the of 2.5 to 4% carbon. The ductility is very low in cast iron. They melt quickly and can be cast into complex shapes. Since casting is the only suitable process applied these alloys, they are known as cast irons. By proper alloying, good foundry control and appropriate heat treatment, the properties of any type of cast iron may be varied over a wide range. The physical properties of the cast iron will greatly influenced by the shape distribution of the free carbon particles. The common cast irons are brittle, have lower strength properties and can be cast more rapidly than most steels. Nodular cast iron, white cast iron, gray cast iron, malleable cast iron, and alloyed cast iron are different type of cast irons [3].

2.2 DUCTILE IRON

If coke had not been used for melting iron and if highly pure ores have been used then ductile iron would have been accepted as normal form of iron [4].Ductile iron is also known as nodular iron, spheroidal graphite iron and spherulitic iron in which graphite is present in tiny balls or spheroids [3]. Because of the graphite is in the form of roughly spherical, which gives these materials their name and ductility significantly improved so alternative name is ductile cast iron. The castability, corrosion resistance, machinability and abrasive resistance are similar to the flake graphite grades but tensile elongation as high as 17% [4].

2.3 BACK GROUND

Ductile cast irons represent a success in 20th century metallurgical research. These irons were developed independently in approximately 1948 at the International Nickel Company (INCO) in the United States and at the British Cast Iron Research Association (BCIRA) in England. Both groups discovered that by keeping the sulfur and phosphorus levels low and adding very small amounts of a key chemical element, the shape of the graphite could be changed from the interconnected flakes of gray irons into isolated spheres (usually called spheroids) of graphite. 6 The INCO team showed that the effect was produced by the addition of only 0.02 to 0.1% Mg, and the BCIRA team by the addition of only 0.02 to 0.04% Ce (the rare earth metal of atomic number 58) [5].

2.4 **PRODUCTION OF SG IRON**

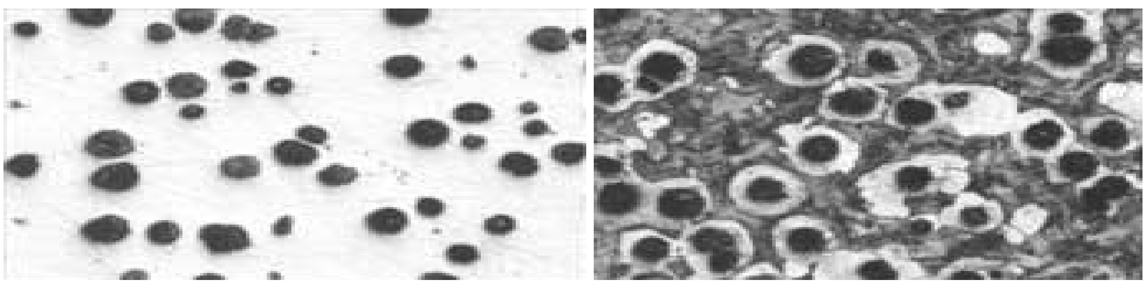
Irons are produced directly by the solidification of a melt containing sufficient silicon to ensure graphite formation, after careful removal of sulphur and oxygen. Magnesium additions to the bath tie up sulphur and oxygen and radically change the graphite growth morphology. Magnesium reacts with the oxygen to form highly stable MgO, which floats to the surface and can be skimmed off. The oxygen content is reduced from typical levels of 90-135ppm to about15-35ppm. Magnesium also reacts with the sulphur to produce MgS which again floats to the bath surface, but less stable than the oxide. Since magnesium has low solubility in the metal and is volatile, the reactions can become reversible if losses are too great. Silicon in the form of ferro silicon is generally added to provide additional deoxidation. Other elements from groups 1A, 11A and 111A can be also being employed to tie up oxygen and sulpher. In particular cerium forms highly stable oxides and sulphides and less volatile than magnesium, with which it is used in combination. Some of the inclusions formed by the inoculants act as nuclei for the graphite and are found at the center of the nodules. The simplest explanation of the spherodising effect of inoculants such as magnesium is that oxygen and sulphur are absorbed preferentially on the hexagonal planes of graphite, leading to the lamellar morphology. The removal of sulpher and oxygen by the inoculants allows more isotropic growth. A careful choice of alloying additions is used to appropriately adjust the deoxidation, graphitizing and nucleation effects [4].

2.5 **CHEMICAL COMPOSITION**

The main common elements of cast iron are carbon and silicon. The amount of graphite or Fe_3C increases with high carbon content . High silicon and carbon content increases the castability of the iron as well as its graphitization potential. The Mn content is a function of the desired matrix. Typically, it is low value of 0.1% for ferrule irons and a high value of 1.2% for pearlitic irons, because Mn is a strong pearlite promoter. From the minor elements, phosphorus and sulfur are the most common and are always present in the 7 composition. They can be high value of 0.15% for low-quality iron and are quite less for high-quality iron, such as ductile iron or compacted graphite iron [6]. The main effect of chemical composition in nodular (ductile) iron is on graphite morphology. The carbon equivalent has only a mild effect on the properties and structure of ductile iron, because it affects graphite shape considerably less than in the case of gray iron. Nevertheless, to avoid high chilling tendency, excessive shrinkage, high impact transition temperature or graphite flotation, optimum amounts of silicon and carbon must be selected. Minor elements can appreciably alter the structure in terms of chilling tendency, graphite morphology, and matrix structure. Minor elements can promote the spheroidization of graphite or can have an adverse effect on graphite shape [6]

2.6 STRUCTURE

The difference between grey iron and ductile iron is the morphology of graphite particles which take on a almost spherical or nodular form after suitable treatments are made to the melt. The major micro structural constituents of ductile iron are the morphological forms taken by carbon and the continuous metal matrix in which the carbon and/or carbide are dispersed. The following important microstructural components are found in ductile iron [7].



(a) (b)

Fig2.6. Mirostructure of ductile iron (a) unethed (b) nital etched: 100X [19]

2.6.1 GRAPHITE

The graphite is the stable form of pure carbon in cast iron. Its important physical properties are low density, low hardness, high thermal conductivity and lubricity. Graphite shape, which can vary from flake to spherical, plays a significant role in determining the mechanical properties of ductile irons. Ductile iron is characterized by having all of its graphite occurs in microscopic spheroids. Although this graphite contains about 10% by volume of ductile iron, its compact spherical shape decreases the effect on mechanical properties [8].

2.6.2 FERRITE

Ferrite is the purest iron phase in a cast iron. In conventional Ductile Iron ferrite produces lower hardness and, but high ductility and toughness. In Austempered Ductile Iron (ADI), extremely fine grained acicular ferrite provides an exceptional combination of toughness and high strength with good ductility. Generally the strength properties of ferritic ductile iron are increased by the elements, which are in the solution. With the exception of carbon, all the elements increase hardness and tensile strength. An example of the extent to which ferrite is impact by solid solution strengthening is illustrated for the elements nickel and silicon [8].

2.6.3 **PEARLITE**

Pearlite is produced by eutectoid reaction. Pearlite is an intimate mixture of lamellar cementite in a matrix of ferrite. A common content of cast irons; pearlite contribute a combination of higher strength with a corresponding reduction in ductility which meets the requirements of many engineering applications [8]

2.6.4MARTENSITE

It is a supersaturated solid solution of carbon in iron produced by rapid cooling. In the untempered condition it is very brittle and hard. It is normally “tempered”-heat treated to reduce its carbon content by the precipitation of carbides-to contribute a controlled combination of high strength wear resistance and ductility [8].

2.6.5 AUSTENITE

Generally a high temperature phase consisting of carbon dissolved in iron, it can exist at room temperature in austempered cast iron and austenitic. In austenitic irons, austenite is stabilized by nickel in the range of 18-36% [28]. In austempered irons, austenite is formed by a combination of rapid cooling which suppress the formation of pearlite and the supersaturation of carbon during austempering, which depress the start of the austenite-to-martensite transformation far below room temperature. In austenitic irons, the austenite matrix contribute ductility and toughness at all temperatures, good high temperature properties and corrosion resistance, especially under thermal cycling conditions. In austempered ductile iron stabilized austenite, in 9 Volume 15 fractions up to 40% in lower strength grades, increases toughness and ductility response to surface treatments such as fillet rolling [8].

2.6.6 BAINITE

Bainite is a mixture of ferrite and carbide, which is produced by alloying or heat treatment [8]. During isothermal transformation, as the phase transformation progresses, austenite transforms to bainitic ferrite by rejecting carbon to the austenitic region. For short austempering time, the formation of martensite cannot be prevented during the subsequent cooling from the austempering temperature to the normal room temperature.

2.7 **TYPES OF DUCTILE IRON**

With a high composition of graphite nodules present in the structure, mechanical properties are determined by the ductile iron matrix. The significance of matrix in controlling mechanical properties is emphasized by the use of matrix names to assign the following types of Ductile Iron [7, 8].

2.7.1 **FERRITIC DUCTILE IRON**

Graphite spheroids in a matrix of ferrite provide an iron with good ductility and affected resistance and with a yield and tensile strength equivalent to low carbon steel. Ferrite ductile iron can be produced as-cast but may be given an annealing heat treatment to ensure maximum ductility and low temperature toughness [7, 8].

2.7.2 FERRITO- PEARLITIC DUCTILE IRON

Generally the grade of ductile iron and are normally formed in the as-cast condition. The graphite spheroids are in a matrix containing both pearlite and ferrite. Properties are intermediate between ferritic and pearlitic grades, with good machinability and low production costs [7, 8].

2.7.3 PEARLITIC DUCTILE IRON

Graphite spheroids in a matrix of pearlite result in an iron with good wear resistance, high strength and moderate ductility and impact resistant. Machinability is also higher to steels of comparable physical properties. The three types of Ductile Iron are usually used in the as-cast condition, but ductile iron can also be alloyed/or heat treated to provide the following grades for a wide range of additional applications [7, 8].

2.7.4 **MARTENSITIC DUCTILE IRON**

Using sufficient alloy additions to avoid pearlite formation, and a temper-and-quench heat treatment forms this type of ductile iron. The resultant tempered martensite matrix improves very wear resistance and high strength but with lower levels of ductility [7, 8].

2.7.5 **AUSTENITIC DUCTILE IRON**

Alloyed to form an austenitic matrix, this ductile iron offers good corrosion and oxidation resistance, and good strength and dimensional stability at elevated temperatures [7, 8].

2.7.6 **AUSTEMPERED DUCTILE IRON (ADI)**

ADI, the most current addition to the ductile iron family, is a sub-group of ductile iron produced by giving conventional ductile iron a special austempering heat treatment. ADI is twice as strong as pearlitic ductile iron; ADI still retains high toughness and elongation. This combination provides a material with superior wear resistance and fatigue strength [7, 8].

2.8 FACTORS THAT AFFECT THE PROPERTIES OF THE DUCTILE IRON

Ductile iron is a special kind of material which exhibits a good combination of strength with ductility ensuring its huge application in heavy engineering industries. This is due to very typical microstructure owing to its chemical composition, heat treatment practice and processing variables. Some lists of important constituents which are responsible for its typical mechanical properties are discussed below

2.8.1 **EFFECT OF GRAPHITE SHAPE**

As expected from dramatic differences in mechanical properties between Ductile and Gray Irons, that modularity plays a significant role in determining properties within the Ductile Iron family. The relationship between modularity and Dynamic Elastic Modulus not only emphasizes the strong effect of modularity on DEM, but also indicates that DEM values formed by sonic testing can be used to measure modularity (graphite volume and nodule count should be relatively constant). Nodularity, and the morphology of the non-spherical particles produced as modularity decreases, exerts a strong influence on the yield and tensile strengths of Ductile Iron. The relationships between strength and nodularity for ferritic irons in which modularity has been changed by two methods: through magnesium control, or through lead control. When nodularity is decreased by reducing the amount of residual magnesium (the most common spheroidizing agent used in commercial Ductile Iron) the nodules become elongated, but do not become sharp or "spiky". The result is a 10% decrease in yield strength and a 15% decrease in tensile strength when modularity is reduced to 30%. Small additions of lead reduce modularity by producing inter granular networks of "spiky" or plate-like graphite which result in dramatic reductions in tensile properties. The influence of nodularity on pearlitic Ductile Irons can be determined by comparing the tensile properties, at constant carbide levels, of irons with nodularities of 90, 70 and 40%. Compared to the Magnesium controlled loss of nodularity for the ferritic iron, the pearlitic iron is much more sensitive to reduced nodularity. Second, at less carbide levels typical of good quality Ductile Iron, there is relatively minute loss of strength as the nodularity decreases to 70% but as nodularity degenerate further, strength decreases more rapidly. The influence of nodularity on elongation can be assumed by considering the effect of nodularity on the difference between the yield and tensile strengths, which is proportional to elongation. Both

Pb and Mg controlled losses in nodularity decrease the difference between the tensile stresses and yield, indicating that loss of nodularity results in reduced elongation. The dramatic decrease in tensile strength produced by lead control indicates that the formation of intercellular, spiky graphite can severely embrittle the ductile iron. Designers can virtually remove the influence of nodularity on tensile properties by indicting that the nodularity should exceed 80-85% and that there should be no intercellular flake graphite. These conditions can be met easily by good production practices which assure good nodularity through Mg control and avoid flake or spiky graphite by a combination of controlling flake-producing elements and removing their influence through the use of small additions of cerium [8].

2.8.2 **EFFECT OF NODULE COUNT**

Nodule Count, expressed as the number of graphite nodules/mm^2, also affect the mechanical properties of Ductile Iron, although not as strongly and directly as graphite shape. Normally, high nodule count specifies good metallurgical quality, but there is a maximum range of nodule count for each section size of casting, and nodule counts in overabundance of this range may result in a degradation of properties. Nodule count per sec does not strongly impact tensile properties, but it has the following effect on microstructure, which can significantly influence properties, Nodule count effect the pearlite content of as-cast Ductile Iron. Increasing the nodule count decreases strength, decreasing pearlite content and increasing elongation. Nodule count impact carbide content. Increasing the nodule count increases ductility, tensile strength and machinability by decreasing the volume fractions of chill carbides, aggregation carbides, and carbides associated with "inverse chill". Matrix homogeneity is affected by nodule count. Increasing the nodule count produces a more and finer homogeneous microstructure. This refinement of the matrix structure decreases the segregation of toxic elements which might form intercellular carbides, degenerate graphite or pearlite.

Nodule count affects graphite shape and size. Increasing nodule count results in a decrease in nodule size which improves fatigue, tensile and fracture properties. Inoculation practices used to enhance nodule count often make the nodules more spherical. Thus, high nodule count is generally associated with enhanced nodularity [8].

2.8.3 **EFFECT OF MATRIX**

In Ductile Irons with consistent nodule count and modularity and low carbide content and porosity, mechanical properties are determined primarily by the matrix constituents and their hardness. For the most common grades of Ductile Iron, the matrix consists of ferrite and/or pearlite. In Ductile Iron, ferrite is the purest iron phase. It has low hardness and strength, but high toughness and ductility and good machinability. In a matrix of ferrite, pearlite is an intimate mixture of lamellar cementite. Compared to ferrite, pearlite provides a combination of higher hardness and strength and lower ductility. The mechanical properties of ferritic/pearlitic Ductile Irons are, therefore, determined by the ratio of ferrite to pearlite in the matrix. This ratio is controlled in as-cast condition by controlling the content of the iron, taking into account the cooling rate of the casting. It can be controlled by an annealing heat treatment to produce by normalizing to maximize the pearlite content or a fully ferritic casting [8].

2.8.4 **EFFECT OF SILICON**

Silicon increases the performance of Ductile Iron at high temperatures by stabilizing the ferritic matrix and obtaining a silicon-rich surface layer which inhibits oxidation. Stabilization of the ferrite phase reduces elevated temperature growth in two ways. Firstly, silicon raises the critical temperature at which ferrite transforms to austenite. The critical temperature is considered to be the upper limit of the desired temperature range for ferritic Ductile Irons. Above this temperature the contraction and expansion associated with the transformation of ferrite to austenite can distort the casting and cracking of the surface oxide layer, reducing oxidation resistance. Second, the strong ferritizing behaviour of silicon stabilizes the matrix against the production of carbides and pearlite, thus reducing the growth associated with decomposition of these phases at high temperature. The oxidation protection offered by silicon increasing with 4% increasing Si content. Silicon levels above 4% are enough to avoid any significant weight gain after the production of an initial oxide layer [10].

2.8.5 EFFECT OF MOLYBDENUM

Molybdenum, whose beneficial effect on the stress-rupture and creep properties of steel is well known, also has a similar effect on Ductile Irons. Addition of 0.5 % Mo to ferritic Ductile Iron produces significant increases in stress rupture and creep strengths, resulting in high temperature properties that are equivalent to those of cast steel containing 0.2 % C and 0.6 % Mn [10].

2.8.6 EFFECT OF MANGANESE

The decomposition of austenite to pearlite in spheroidal graphite (SG) cast iron or ferrite plus graphite is known to depend on a number of factors among which are the nodule count, the cooling rate, and the alloying additions (Si, Mn, Cu etc.).The detrimental effect of Mn on the growth kinetics of ferrite during the decomposition of austenite in the stable system is explained in terms of the driving force for diffusion of carbon through the ferrite ring around the graphite nodules. Finally, it is found that copper can have a pearlite promoter role only when combined with a low addition of manganese. As it is a mild pearlite promoter, with some required properties like proof stress and hardness to a small extent, Mn retards the onset of the eutectoid transformation, decreases the rate of diffusion of C in ferrite and stabilizes cementite (Fe_3C), but the problem here is the embrittlement caused by it, so the limiting range would be 0.18-0.5%. [8, 9, 10]

2.8.7 **EFFECT OF COPPER**

The effect of various additions of copper and the cooling rate on the temperature of the onset of the metastable and stable eutectoid reactions describes the conditions for the growth of ferrite and of pearlite. These reactions can improve only when the temperature of the alloy is below the lower boundary of the ferrite/austenite/graphite or ferrite/austenite/cementite related three-phase field. Copper is a strong pearlite promoter. It increases the proof stress with also the tensile strength and hardness with no embrittlement in matrix. So in the pearlitic grade of the ductile iron the copper is kept between 0.4-0.8percent and is a contaminant in the ferritic grade [8, 9, and 10].

2.8.8 **EFFECT OF NICKEL**

It helps in increasing the U.T.S without affecting the impact values .So it can be used in the range of 0.4-2.0%. It strengthens ferrite, but has much less effect than Silicon in reducing ductility. As a Mild pearlite promoter, increases proof stress but little effect on tensile strength, but there is the danger of embrittlement with the large additions, in excess of 2%. Due to the high cost it is generally present as traces in the matrix. The irons treated with nickel have nodular graphite in a matrix of austenite with rather more carbide than the untreated irons [8, 9, 10].

2.9 AUSTEMPERED DUCTILE IRON

2.9.1 Austempering

The austempering process was first developed in the early 1930's as a result of work that Bain, et al, was conducting on the isothermal transformation of steel. In the early 1940's Flinn applied this heat treatment to cast iron, namely gray iron. In the 1950's, both the material, ductile iron, and the austempering process had been developed [11].

Process

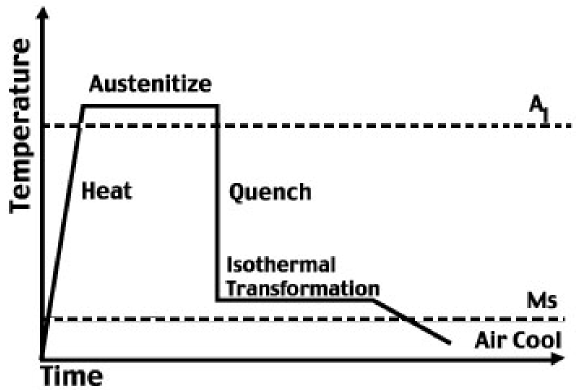


Fig2.9.1.1 Schematic representation of Austempering process.

1) In a muffle furnace, heat the casting to austenitizing temperature (850-900^{O}C)

2) Maintained at austenitizing temperature to dissolve carbon in austenite.

3) Quench quickly to prevent pearlite.

4) Hold at austempering temperature (232-400^{0}C) in molten salt bath for isothermal transformation to ausferrite [12].

Consistent control of times and temperatures throughout the entire process

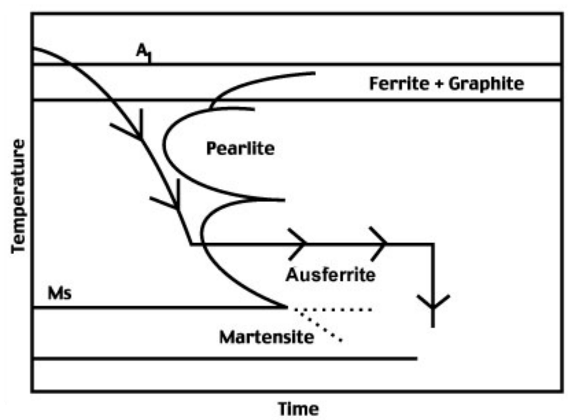


Fig. 2.9.1.2 Schematic representation of transformation during austempering process

Control of time and temperature on the process [12]

1) Initial austenitizing times and temperatures (850° to 900° C.) are controlled to ensure formation of very small grain austenite and uniform carbon composition in the matrix. The exact temperature is grade dependant.

2) Quench time should be controlled within a few seconds, to prevent formation of pearlite around the carbon nodules, which would reduce mechanical properties. Quench temperature (232° to 400°C.) must stay above the point of martensite formation.

2.9.2 AUSTENITIZING

The austenitizing temperature controls the carbon composition of the austenite which, in turn, influence the structure and properties of the austempered casting. High austenitizing temperatures raise the carbon content of the austenite, increasing its hardenability, but building transformation during austempering more problematic and potentially reducing mechanical properties after austempering. (The higher carbon austenite requires a longer time to transform to ausferrite). Reduced austempering temperatures generally produce ADI with the best properties but this requires close control of the silicon content, which has a significant effect on the upper critical temperature of the Ductile Iron.

Fig 2.9.2.1.: Standardization of salt bath temperature by multimeter

Fig2.9.2.2: Austemering process carried out in the furnace

3) In the austempering stage which follows austenitizing, the temperature of the final salt bath must also be closely controlled. The austempering step is also exactly time-controlled, to prevent over-or under-processing. By the end of this step, the desired ADI ausferrite structure has developed [12].

Austenitizing time should be the minimum required to heat the entire part to the desired austenitizing temperature and to saturate the austenite with the equilibrium level of carbon, (typically about 1.1-1.3%). In addition to the casting section type and size, the austenitizing time is impacted by the chemical composition, the austenitizing temperature and the nodule count [13].

2.9.3 **AUSTEMPERING**

Austempering is fully adequate only when the cooling rate of the quenching apparatus is enough for the section size and hardenability of the component. The minimum rate of cooling is that required prevent the formation of pearlite in the part during quenching to the austempering temperature. The critical characteristics are as follows:

1. Transfer time from the austenitizing environment to the austempering environment
2. The quench rigor of the austempering bath
3. The maximum section type and size of casting being quenched
4. The castings hardenability

5. The mass of the load relative to the quench bath.

The use of a correctly designed austempering system with a suitably high quench rigor, and the correct loading of castings, cans derease hardenability requirements of the casting resulting in significant savings in alloy costs [13].

2.10 **AUSTEMPERED DUCTILE IRON**

Austempered ductile iron is the most recent addition of the ductile iron family. It is prodused by giving conventional ductile iron to austmepering heat treatment [13]. Unlike conventional "as-cast" irons, its properties are achieved by heat treatment, not by specific addition. Therefore the only prerequisite for a good ADI is a quality ductile iron [15]. Austempered Ductile Iron (ADI) offers the best combination of low cost, good machinability, design flexibility, high strength-to-weight ratio and good toughness, wear resistance and fatigue strength properties. Because ADI can be cast like any other member of the Ductile Iron family it offers all the production advantages of a conventional Ductile Iron casting. Succeeding it is subjected to the austempering process to produce mechanical properties that are higher to conventional ductile iron, cast and forged aluminum and many cast and forged steels [17]. The mechanical properties of properties of the ductile iron and austempered ductile iron are primarily determined by the metal matrix. The matrix in conventional ductile iron is controlled by mixture of pearlite and ferrite. The properties of austempered ductile iron is due to its unique matrix of acicular ferrite and carbon stabilized austenite, is called ausferrite. The austempering process has been utilized since the 1930 on cast and wrought steels but this process first commercially applied to ductile iron in 1972 [14].

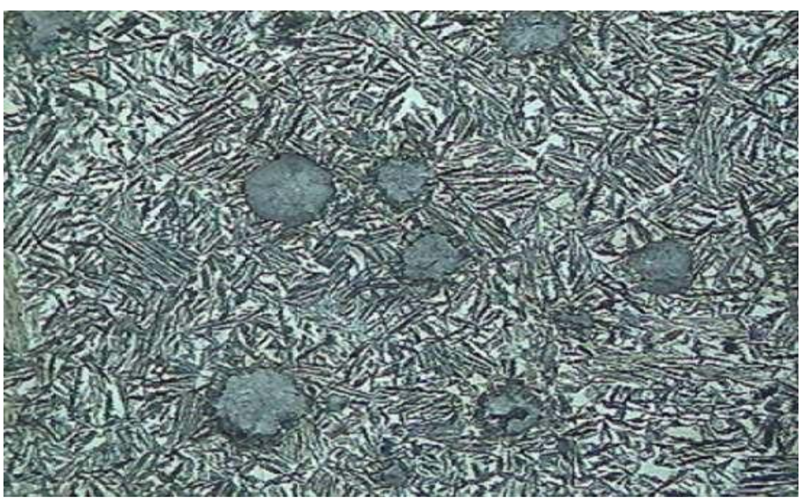
2.10.1 **MICROSTRUCTURE**

When subjected to the austempering heat process ductile cast iron undergoes a remarkable transformation. A new microstructure (ADI) results with capability superior to many traditional, high performance, ferrous and aluminum alloys. To optimize ADI properties for a particular application the austempering parameters must be carefully selected and controlled. Castings are initially austenitised to dissolve carbon, then quenched rapidly to the austempering temperature to prevent the formation of deleterious pearlite or martensite.

While the casting is maintained at the austempering temperature nucleation and growth of needle shape ferrite occurs, accompanied by rejection of carbon into the austenite. The resulting microstructure, known as "Ausferrite", gives ADI its special attributes. Ausferrite exhibits twice the strength for a given level of ductility compared to the pearlitic, ferritic or martensitic structures formed by conventional heat treatments. Because the carbon rich austenite phase is stable in Austempered Ductile Iron it improves the bulk properties. Moreover, while the austenite is thermodynamically stable, it can undergo a strain-induced transformation when locally stressed, forming islands of hard martensite that enhance wear properties. This behavior contrasts with that of the metastable austenite retained in steels, which can transform to brittle martensite [18].

2.10.2 COMPOSITION

In many cases, the composition of an ADI casting differs minute from that of a conventional Ductile Iron casting. When choosing the composition, and hence the raw materials, for both ADI and conventional DI, consideration should be given initially to limiting elements which adversely affect casting quality through the production of nonspheroidal graphite, or the formation of carbides and inclusions, or the promotion of shrinkage. The second consideration is the control of silicon, carbon and the important alloying elements that control the hardenability of the iron and the properties of the transformed microstructure.



Fg2.10.2. Microstructure of austempered ductile iron [18]

When determining the alloying requirements both the section size and type and the severity (or speed) of the austempering quench must be considered [13]. For a typical salt quench with agitation section sizes up to about 3/8 inch (10 mm) can be successfully through hardened without pearlite with even unalloyed Ductile Iron. For a highly agitated austemper quench with water saturation section sizes of up to ¾ inch (20 mm) can be through hardened with no additional alloying. To cast heavier section size selective alloying is required to through harden the parts and prevent pearlite in the heat treated microstructure [13].

2.11 EFFECT OF ALLOYING ELEMENTS

2.11.1 CARBON

Increasing carbon content in the range 3 to 4% increases the tensile strength but has negligible effect on elongation and hardness. Carbon content must be controlled within the range 3.6-3.8% except when deviations are required to provide a defect-free casting [13-14].

2.11.2 MANGANESE

Manganese can be both a harmful and a beneficial element. It strongly enhance hardenability, but during solidification it segregates to cell boundaries where it produces carbides and retards the austempering reaction. As a result, for castings with either section sizes greater than 3.4 in. (19mm) or low nodule counts, Mn segregation at cell boundaries can be sufficiently high to produce carbides, shrinkage and unstable austenite. These microstructural defects and inhomogeneities reduce machinability and mechanical properties. To enhance properties and reduce the sensitivity of the ADI to nodule count and section size, it is advisable to restrict the manganese level in ADI to less than 0.3%. The use of highly pure pig iron in the ADI charge offers the twin advantages of reducing the manganese in the steel scrap to useful levels and controlling undesirable trace elements [13-14].

2.11.3 NICKEL

Up to 2% nickel may be used to enhance the hardenability of ADI. For austempering temperatures below 675oF (350^{o}C) nickel reduces tensile strength slightly but increases ductility and fracture toughness [13-14].

2.11.4 MOLYBDENUM

In ADI, molybdenum is the most potent hardenability agent and may be required in heavy section castings to avoid the formation of pearlite. However, both ductility and tensile strength decrease as the Mo content is increased beyond that required for hardenability. This degradation in properties is probably caused by the segregation of molybdenum to cell boundaries and the formation of carbides. The molybdenum content should be restricted to not more than 0.2% in heavy section castings [13-14].

2.12 ADVANTAGES OF AUSTEMPERED DUCTILE IRON:

ADI provides high strength, superior wear qualities, good fatigue properties, excellent toughness, and cost-effectiveness.

An Overview

Austempered Ductile Iron is a heat treated form of as-cast ductile iron. The main aim in the in heat treatment process was to improve strength and toughness of ferrous alloys. Now a days ADI burst onto the scene with a host of creative and innovative casting solutions. ADI provides a high strength-to-weigth material at a component price that is typically 20 % less than that of steel. The ADI have the advantages that the base iron is readily machinable before heat treatment allowing hard wearing close tolerance and matings parts to be produced. The physical property also increases as per desired and expected. The following lines indicate the physical behavior of ADI [43].

Tensile: Twice the tensile strength of ductile iron, work gardens

Wear: Wear resistance superior to steel at any hardness level, ideal for high abrasion applications.

Weight: 10 % lighter than steel

Cost: Energy savings over steel, Easier to machine than steel reduced machining allowances and near net shaped castings means even less machining [44].

Sustainability (Green-ness of ADI)

The sustainability or green-ness of any product or material can be measured by its use of energy and its effect on the ambient (radiation, emissions etc) environment during its life. The net energy and ambient effect is mitigated by the recyclability of all of the components of an engineering device [45]. A new term (embodied energy) has been employed by the architectural community to define the total energy resident in a manufactured component. This concept can be employed for inventorying and quantifying the energy content in an assembly or device. A basic idea can be understood from all the designers in engineering community that to reduce the weight (mass reduction) for sustainability. Engineers and designers are often surprised when life-cycle energy comparisons are made that show ferrous metals to be more sustainable than many polymers or any light weight materials [46, 47]. Today, for example, ferrous materials (steel and iron) make up approximately 62% of the total mass of a light vechile and 64% of the mass of a class 8 truck tractor and trailer largely because of their low cost and recyclability.

2.12.1 FATIGUE STRENGTH

ADI's fatigue strength is typically 50% higher than that of standard ductile irons. It can be further increased by fillet rolling or shot peening. The low hardness grades of ADI work well in structural applications.

2.12.2 TOUGHNESS

ADI's excellent impact and fracture-toughness properties make it ideal for applications such as ground-engaging tools**.**

2.12.3 LESS WEIGHT

ADI is 2.3 times stiffer and weighs only 2.4 times more than aluminum. Steel is 10% more dense than ADI. Therefore, when compared the relative weight per unit of yield strength of ADI with that of various steels and aluminums, it is easy to see the design and engineering advantages inherent in ADI.

2.12.4 WEAR CHARACTERISTICS

The higher hardness grades of ADI are outstanding for wear applications. Unlike case-hardened materials, usually the ADI is uniformly hardened throughout the part. Also, when stressed ADI work-hardens. This forms a thin surface of very hard martensite where wear resistance is most necessary.

2.12.5 COST-EFFECTIVENESS

Steel forgings or castings are usually 15% to 20% more costly than ADI. It is the most economical way of obtaining yield, fatigue strength or tensile. ADI often contest favorably with heat-treated and alloy steels for heavy-duty applications where reliabilty is crucial. It is a desiable upgrade from standard grades of ductile iron. In some cases it replaces nickel-chrome iron and manganese steel. Because of ADI's high strength-to-weight ratio, it has even replaced aluminum where the design allows reduced section sizes [14].

2.13 APPLICATIONS OF AUSTEMPERED DUCTILE IRON

The development and commercialization of Austempered Ductile Iron (ADI) has contibuted the design engineer with a new group of cast ferrous materials which offer the abnormal combination of mechanical properties equivalent to forged and cast steels and production costs similar to those of conventional Ductile Iron. ADI also contribute the designer with a wide range of properties, all formed by varying the heat treatment of the same castings, ranging from 125 ksi (870 MPa) tensile strength with 10-15% elongation, to 1-3% elongation with 250 ksi (1750 MPa) tensile strength . Although initially hindered by lack of information on properties and successful applications, in many applications ADI has become an established alternative and were previously the particular domain of steel castings, forgings, weldments, powdered metals and aluminum forgings and castings [22].

2.13.1 HEAVY TRUCK AND BUS COMPONENTS

Economic growth drives the need to move heavier loads over longer distances, resulting in some difficult engineering challenges and more time between vehicle maintenance. Many years ago heavy truck industry recognised the potential benefits of Austempering solutions. To introduce innovative light weight, high performance parts manufacturers took advantage of the versatility of ADI. Hypoid Ring, Diesel Engine Timing Gears, and Pinion Gears, Jack Stand Gears, Wheel Hubs, Suspension Brackets these are some components which are manufactured by using austempering ductile iron [18-22].

2.13.2 RAILWAY

The Railway industry is constantly looking to improve its products and the safety and efficiency of rail transport. The railroad industry uses ADI for suspension top caps, housings and friction wedges, track plates, nipper hooks, repair vehicle wheels, and car wheels [18-22].

2.13.3 CONSTRUCTION EQUIPMENT

Hard working and heavy duty, construction equipment can benefit greatly from the use of wear resistant, tough Austempered Irons and Steels. Whether for ground engaging components such as engine or bucket teeth and powertrain parts, ADI and other Austempered materials can improve the performance of your equipment [18-22].

2.13.4 LIGHT VEHICLE

The automotive industry is constantly looking to enhance performance, and decrease the cost and weight of the vehicles they produce. Austempered materials have a proven track record of contributing strength and dependability for suspension systems, safety components, and drivetrain applications [18-22].

2.13.5 MISCELLANEOUS INDUSTRIAL

Miscellaneous industrial applications include knuckles, brackets, lever arms , shafts, cams, sway bars, sleeves, clevises, conveyor components, sprockets, , bushings, rollers, molding line components, jack components, fixtures, gears, deck plates, and all sorts of power transmission and structural components [18-22].

2.13.6 AGRICULTURAL

Agricultural applications for ADI include plow points, till points, seed boots, ammonia knives, gears, sprockets, trash cutters, knotter gears, tractor wheel hubs, rasp bars, disk parts, bell cranks, ripper points, lifting arms, and a great variety of parts for planters, plows, sprayers and harvesters [22].

2.13.7 SPORTING GOODS

Even the sports goods industry has included ADI for its high strength to weight and superior wear resistance. Bobsleigh runners, Sword blades, Gun components are manufacturing by using austempered ductile iron [18].

2.13.8 DEFENSE

The defense industry has slowly adopted ADI; however some of the applications include ordnance, track links, armor, and various hardware for trucks and armored vehicles [22].

2.13.9 GEARS/SHAFTS/POWERTRAIN

For high performance gear and power train manufacturers, Austempered materials offer greater wear resistance, reduced noise, improved bending and contact fatigue, as well as increased strength and durability, Hypoid Ring and Pinion Gears, CV Joints, Diesel Engine Timing Gears, Off-Highway Drive Axles, Ring Gears, Sprockets, Differential Housings, Gear Housings, Wheel Hubs etc are prepared by using austempered ductile iron [18].

CHAPTER 3

DISCUSSIONS ON PREVIOUS WORKS

3.1 DISCUSSIONS ON PREVIOUS WORKS

From the available literatures, it is proved that many attempts were made to understand and predict the behaviors of austempered ductile iron that includes the study of ausferrite matrix structure and the response of matrix structure to heat treatment, structure and properties correlation, and its mechanical properties with different variables and possible applications. A brief review of some literatures in these areas is studied here under.

J.Zimba, D.J. Simbi, E. Navara have studied the abrasive wear and mechanical properties of the austempered ductile iron and compared these properties with the quenched and tempered steel. In this regard they have taken one type of ductile iron sample and two types of steel samples and austmpered the ductile iron sample at different temperatures and times, and steel samples were quenched & tempered at different temperatures. They observed that as the austempering temperature increases so does the ferrite lath spacing and the volume fraction of retained austenite. In mechanical properties, the tensile strength and hardness decrease with austempering temperature while the elongation and impact toughness indicate appreciable increase as the austempering temperature is increased. The good wear resistance provided by austempered ductile iron despite the low initial hardness can be attributed to the surface transformation of retained austenite to martensite during abrasion, i.e. during abrasion; there is a surface transformation of retained austenite to martensite. Due to this the surface hardness and wear resistance of austempered ductile iron increase [24].

Uma Batra, S.Ray and S.R.Prabhakar studied on the variation in the austempered microstructure, the porosity of retained austenite, the average carbon content of retained austenite, their product and the size of bainitic ferrite needles with austempering temperature for 0.6% Cu alloyed ductile iron. In this work they have taken copper alloyed ductile iron specimens and austempered at different temperatures and times. They observed that increasing austempering temperature changes the bainite morphology from lower bainitic to upper bainite. The average austenite volume fraction of austenite, its carbon content, and the size of bainitic ferrite also increase with increasing austempering temperature. Increasing the austempering time initially increases the amount of retained austenite and its carbon content, both of which then reach a plateau. The plateau extends over a period of stability of retained austenite, after which there is a decrease of both [26].

Olivera Eric, Dragan Rajnovic, Slavica, Leposava Sidjanin, T.Jovanovic studied on the macrostructure and fracture of two types of austempered ductile iron, one is alloyed with copper and another one is alloyed with copper and nickel and observed the impact of copper and copper plus nickel on the microstructure and impact properties of the two types austempred ductile irons. They predicted that addition of copper plus nickel delays the transformation kinetics of the residual austenite resulting in a shift of the maximum of porosity of retained austenite to 3 hours of austempering, compared to 2 hours in austempered ductile iron alloyed with copper. In the same time, they observed higher maximum value of the volume fraction of retained austenite in austempered ductile iron alloyed with copper plus nickel. In the same austempered ductile iron a substantial plastic deformation at the peak of impact energy is associated with the highest volume fraction of retained austenite. So they have been predicted that the volume fraction of retained austenite strongly effects impact energy of both irons, i.e. with content retained austenite up to maximum value impact energy increases, then a decrease occurs with the decrease of retained austenite [23].

F.Y. Hung, L.H. Chen, T.S. Lui studied the particle erosion of upper bainitic austempered ductile iron. They have taken aductile iron sample and austempered at 420^0C and at different times. Then these upper bainitic austempered ductile iron (ADI) specimens were eroded by Al_2O_3 particles of 275μm grid size under the average particle velocity of $73ms^{-1}$. They observed that the austempered specimen of lower austempering time which contains largest amount of retained austenite and no austempered carbide is more erosion resistance than other ADI specimens and the same cast iron of other common matrix structures. If austempering time is increased then brittle cracks will induce at normal impact and shift the impact angle of maximum erosion rate to a higher one. They also predicted that carbide will form upon the particle impingement and retained austenite is not only phase to transformed during the erosion process but also may be possible for the bainitic ferrite because its carbon concentration is higher than equilibrium[27].

J. Aranzabal, J.M. Rodriguez-Ibabe, I. Gutierrez, , and J.J. UrcolaR have studied on the the effect of the amount and morphology of austenite phase on the mechanical properties (proof stress, ultimate tensile strength (UTS),elongation and toughness) at different austempering parameters. They concluded from their work that the short time treatments lead to deteriorated mechanical properties in accordance with the presence of untempered martensite. The combination of long duration and high temperatures of austempering produces a similar trend associated, in this case, with the decomposition of the austenite, into ferrite plus coarse carbides, that takes place during the heat treatment. At the lowest temperature, the austenite is plastically stable due to the higher carbon content and to the finer distribution of this phase in the microstructure. The bainitic ferrite and the austenite constribute to the proof stress of the material, and the increase of the austenite volume fraction has improved effect on the toughness. The increase of the austenite volume fraction as the treatment temperature increases has two different effects on the material properties: a decrease of the carbon content and a coarser morphology of this phase. After 300^0 C isothermal treatments at intermediate times, the austenite is plastically stable at room temperature and contributes, together with the bainitic ferrite, to the proof stress and the toughness of the material. For austenite volume fractions higher than 25 pct, the proof stress is controlled by this phase and the toughness depends mainly on the stability of austenite. In these conditions (370^0C and 410^0C treatments), the present material provides a transformation-induced plasticity effect, which leads to an improvement in ductility. It is shown that the strain level necessary to initiate the martensitic transformation induced by deformation depends on the carbon content of the austenite. The martensite formed under TRIP conditions can be of two different types: autotempered plate martensite, which forms at room temperature from an austenite with a quasi-coherent epsilon carbide precipitation, and lath martensite nucleated at twin boundaries and twin intersections [30].

M.Nili Ahmadabadi, H,M.Ghasemi and M.Osia have studied the influence of austempering process on the wear behavior of austempered ductile iron ADI. In this work they have taken a 0.75 wt. % Mn ductile iron with different nodule counts was austempered by conventional and successive austempering processes at 315 and 375^0 C for different duration. They are concluded from their sliding wear tests on specimens with optimum mechanical properties austempered by different processes is that the delamination mechanism as a dominant wear mechanism. From the mechanical and wear test results they told that successive austempering process improves both mechanical properties and wear resistance of ADI in comparison with conventional austempering process. The specimens with lower nodule count longer solidification time have lower wear rate than specimens with higher nodule count shorter solidification time. High carbon content retained austenite along with good mechanical properties is supposedly the main reason for improvement of wear resistance of HLAT specimens [33].

U. Batra studied the fracture behavior of copper-alloyed austempered ductile iron using metallography and fractography. She investigated the effect of austempering temperature on the microstructure, mechanical properties, fracture behavior under tensile and impact loading, and fracture mechanism. She concluded from their work is that when the austempering temperature is increased from 270 to 380°C, the volume fraction of retained austenite, the carbon content of the austenite, and the size of the bainitic ferrite needle increase. The morphology of the bainitic ferrite changes from lower to upper. Proof stress, 0.2% of hardness and UTS of the ADI decrease, but the impact energy increases with the increase in austempering temperature from 270 to 380°C. The percent elongation increases with the increase in austempering temperature from 270 to 330°C but decreases on further increase in temperature to 380°C. In ADI austempered at 270°C, the deformation is limited to near the nodule only. However, it spreads into the matrix for ADIs austempered at the higher austempering temperatures of 330 and 380°C. The crack generally initiates from the graphite nodule surface and proceed through the matrix of retained bainitic ferrite and austenite. It normally propagates through bainitic ferrite/austenite interfaces when ferrite makes an angle greater than 45° with the applied load, but it cuts through bainitic ferrite when the cluster of bainitic ferrite makes an angle less than 45° with the applied load. Intercellular segregation and nonmetallic inclusions are the other probable locations for crack growth [36].

C.Z. Wu, Y.J. Chen andT.S. Shih have studied the phase transformation of austmepered ductile iron by microjet impact. For that they have austempered the ductile iron specimens at 320^0C and 360^0C with ultrasonic vibration treatment. They found from their work is that the content and microstructure of retained austenite have a fundamental influence on the mechanical properties of ADI. Good ductility is provided in the matrix microstructure where a large porosity of austenite has been retained and most island-like austenite is uniformly distributed over the matrix, as in the case developed from Ni- and Cu-alloyed ADI. After subjecting to ultrasonic treatment, some island-like austenite is found to undergo a phase transformation of austenite to martensite induced by shear stresses from impact of microjets and shock waves, while some stringer-type austenite is found to precipitate carbides. After the process, microhardness values are increased along with an increased cumulative treatment time. The values obtained in intercellular regions are much higher due to Mn segregation. The stress-induced transformed martensite analyzed by EPMA is found to have a higher content of Mn for island-like austenite, which appears without microcracks, and that having a lower content of Mn usually shows microcracks after ultrasonic treatment. The elastic strain-energy density evaluated from a microjet impact on the surface of ADI varied from 5.1×10^3 to 9.2×10^4 J/m3. The elastic strain energy density of matensite nucleus is about 8.6×10^7 J/m3. Apparently, this estimated elastic strain-energy density is far lower than the energy necessary for homogeneous nucleation of martensite [40].

A.Kutsov, Y.Taran, K.Uzlov, A.Krimmel and M.Evsyukov studied the kinetics of kinetics of bainite transformation under isothermal conditions in Ni-Mn-Cu-Mo alloyed ductile iron. They demonstrated the formation of upper and lower bainite in the ductile iron described by different C-shaped curves. They concluded from their work is that morphology of the bainite changes accordingly: the upper bainite has a feathery-like morphology and the lower bainite has a plate like one. These facts are, probably, a result of different crystallographic shears during the formation of the upper and lower bainites. A comparison of the dilatometrical data with the X-ray results shows that the bainite transformation decreases once the carbon concentration in low carbon austenite reaches a certain value. It is suggested that this concentration corresponds to curve and the composition of high carbon austenite is increasing. It seems to be that the increase of the bainitic α-phase volume fraction results in an increase of the volume fraction of high carbon austenite [35].

Dong Cherng WEN and Tien Shou LEI have studied the mechanical properties and microstructure of low alloyed ductile iron in the upper ausferrite region. For that they have taken the samples of ductile iron alloyed with 0.77% Cu and 0.5% nickel and austenitized at 900^{o}C and austempered at 400^{o}C. They found from their work is that the martenslte content of ADI had a significant influence on its mechanical propertles. As martensite content increased, ductility and toughness decreased obviously. The influence of martensite on reducing mechanical properties coud be eliminated after tempering at 200^{0}C. Ductility and toughness could be increased without decreasing the previous strength, and these strengthening effects were particularly evident at 3-50% martensite content. Tempering at 200^{0}C could shorten the austempering time in getting the same level as the peak values of mechanical properties of ADI treated with single austempering, and could extend the effective range of austempering time. From the observation of mechanical properties and microstructure changes, it was evident that the use of processing window defined by resisitivity curve in selecting the isothermal holding time in austempering was effective and direct. When ductile iron was austempered within this processing window the mechanical properties satisfied the standard requirement were ob tained.

Yoon-Jun Kim, Hocheol Shin, Hyounsoo Park and Jong Dae Lim have studied how the mechanical properties of the austempered ductile cast iron varying with the autempering temperature. For that they have austenitized the samples alloyed with copper and molybdenum at 910^{o}C for one hour and autmepered at 350 and 410^{0}C temperatures. From their work they concluded that Cu and Mo alloyed iron blocks were cast and heat treated. In order to see the effect of austempering temperature on mechanical properties, blocks were austenitized at 910 °C for 90 min, then quenched and held at 350, 370, 390 and 410 °C for 90 min. It was found that the higher austempering temperature, the higher ductility. The highest ductility was obtained from410 °C austempered samples. However, tensile strength was highest for 350°C austempered cast iron. Based upon mechanical property investigations, ADIs produced at higher isothermal tempering temperatures such as 390 °C and 410 °C can be categorized as an ASTM grade1. While those austempered at lower temperatures such as 350 °C and 370 °C can be grouped as ASTM grade 2. Copper and molybdenum addition plays significant role in the formation of ausferrite structure as well as increment of mechanical properties such as tensile strength and hardenability [41].

Uma Batra, S.Ray and S.R.Prabhakar studied the effect of austempering temperature and time on tensile properties such as 0.2% proof stress, ultimate tensile strength (UTS), percentage of elongation, and quality index and these properties have correlated with the structural parameters of the austempered ductile iron microstructure. For that they have a ductile iron containing 0.6% copper as the main alloying element was austenitized at 850 °C for 120 min and was subsequently austempered for 60 min at austempering temperatures of 270, 330, and 380 °C. The samples were also austempered at 330 °C for austempering times of 30-150 min. They concluded from there is that, in Cu-alloyed ADI, when the austempering temperature increases from 270-380 °C, the proof stress and UTS decrease due to the change in morphology of the bainitic ferrite. However, the percentage of elongation and the QI increase monotonically. The proof stress, UTS, and the percentage of elongation, as well as the QI, are relatively low at short tAs, and these values increase as the austempering process progresses. The proof stress may decrease at longer tAs, while the UTS remains, more or less, constant. Austempering the Cu-alloyed ductile iron for 60 min at 270, 330, or 380 °C resulted in an ADI close to the 1200/4, 1050/7, and 850/10 grades of ASTMA 897. The UTS and the percentage of elongation of this ADI alloy that was austempered at 330 °C fall below those specified in the ASTM standard for tAs less than 30 min; however, these properties improve for tAs of 60-150 min [34].

Uma Batra, Subrata Ray, and S.R. Prabhakar studied the effect of alloying elements on the austempering process, austempered microstructure, and structural parameters of two austempered ductile irons (ADI) containing 0.6% Cu and 0.6% Cu +1.0% Ni as the main alloying elements. They used optical metallography and x-ray diffraction to study the changes in the austempered structure. They studied influence of alloying additions on the austempering kinetics using the Avrami equation. They predicted significantly more upper bainite in the austempered Cu-Ni alloyed ADI than in Cu alloyed ADI. The volume fraction of retained austenite, the carbon level in the retained austenite, and the product of retained austenite and carbon content in an austempered structure of Cu-alloyed ADI are higher than in Cu-Ni-alloyed ADI. The austempering Kinetics is slowed down by the addition of Ni [28].

Srinivasamurthy daber, K.S.Ravishankar, P.Prasad Rao have studied the influence of austenitising temperature on the formation of strain-induced martensite in austempered ductile iron. For that they have taken Ductile iron containing 1.5 wt.% nickel, 0.3 wt. % Mo and 0.5 wt.% copper was subjected to austempering treatments which consisted of three austenitising temperatures, namely 850, 900 and 950^{o}C, and three austempering temperatures, namely 300, 350 and 400^{0}C. They were carried out tensile tests under all the heat-treatment parametrs and strain-hardening behaviour was studied by applying Hollomon equation. Microstructures were studied by optical microscopy and X-ray diffraction. They observed that the retained austenite can transform to martensite through a TRIP like phenomenon. The propensity to transform to martensite under strain depends to a large extent on the austenitising temperature. As the austenitising temperature is increased the tendency to transform to martensite increases at all the austempering temperatures. High austenitising temperature together with high austempering temperature forms retained austenite with low stability, and therefore greater tendency to form martensite under strain [32].

C.Valdes, M. Figueroa, M.J. Perez Lopez, and L.E. Ramirez have studied Microstructural features and mechanical properties of austempered ductile iron with duplex matrix unalloyed and alloyed with 1Ni-0.24 Mo by optical microscopy, tensile and impact test. For that they heated the ductile iron specimens to the austenitizing temperature in the range of 780 to 830^0C for 90 minutes and then austempered at 375^0C for 60 minutes. They observed that Ascast microstructure was constituted by a ferritepearlite mixture of the bull-eye type with an average of graphite nodularity of 93%.UTS, elongation and impact strengh strongly depend on amounts of pro-eutectoid ferrite and ausferrite present after heat treatment.Unalloyed and 1Ni-0.24Mo ductile iron treated in the intercritical region between 800 – 830^0C, exhibited the highest impact strength from 140 to 145 J and from 100 to 130 J,respectively, due to presence of duplex matrix structure [38].

A.S.M.A. Haseeb, Md. Mohar Ali Bepari , Md. Aminul Islam, studied the behaviour of ductile iron heat treated by two different procedures, quenching &tempering and austempering to identical matrix hardness. They have taken samples of ductile iron, heat treated (austempered and quenching & tempering) and carried out wear tests using a pin-on-disc type apparatus under dry sliding conditions. They have observed that under all test conditions austempered ductile iron exhibits a better wear resistance than quenched & tempered ductile iron, although both have an identical chemical composition and matrix hardness. The relative superiority of austempered ductile iron becomes even more pronounced at higher load and longer sliding distance. Micro hardness measurement below wear scar reveals that the hardness of austempered ductile iron increases while that of quenched and tempered iron decreases during the wear process [31].

Z.K.Fan and R.E.Smallman have studied the fracture behavior of the austempered aluminum spheriodal graphite iron. For that they have taken the specimens of Aluminum spheriodal graphite iron containing by weight 3.2%C, 2.2%A1, 0.3%Si were austenitised at 950°C for 2 hours and then austempered at 300°C or 400°C for times up to 6 hours, polished and were squeezed to fracture. From the observations they demonstrated that Cracks always originate from graphite nodules in austempered ductile iron. The easiest propagation path of a crack in austempered ductile iron is along the austenite ferrite interfaces and the propagation path of a crack depends on the orientation relationship of bainitic ferrite laths with the applied load direction, and also on whether there is carbide precipitation in the bainitic ferrite laths or at the ferrite austenite interfaces. Carbides precipitated in bainitic ferrite laths promote the passage of cracks through the ferrite laths, but do not appreciable influence the fracture mode and Carbides precipitated at the ferrite austenite interfaces clearly promote crack propagation along the interfaces and change the fracture mode from ductile to cleavage in austempered ductile iron. In the absence of carbide precipitation in the matrix, the fracture mode of austempered ductile iron is typically ductile. Cracks often propagate along the interfaces which lie approximately normal to the applied load direction, but cut through the bainitic ferrite laths which lie parallel to the applied load direction [25].

C.Hakan Gür, Volkan Kilicli, Mehmet Erdogan have studied the mechanical properties of austempered ductile iron achieved through the heat treatment. They conducted in a restricted temperature and time frame called the "processing window". In this study they have investigated MBN response and variations in microstructure and mechanical properties of austmpered ductile iron. MBN measurements are susceptible to the fine evolutions of the austempering stages of austempered ductile iron. Martensite volume fraction linearly decreases and finally disappears with increasing the austempering time while the transformed acicular ferrite contents increases and austenite content decreases. By measuring the MBN parameters, the height and the position of MBN peak , the variations in the microstructure and corresponding changes in tensile strengths, yield and total elongation can be estimated non-destructively [37].

O. Eric, M. Jovanovic, L. Šidjanin and D. Rajnovic studied on the microstructure and mechanical properties of the austempered ductile iron which is alloyed with copper, Nickel and molybdenum. In this work they austenised the samples at 860^{0}C for one hour and then austempered at 320^{O}C and 400^{0}C in the form 0.5 to 5 hours. They observed from their work is that the Austempering at 320^{o}C in the range between 2 and 5hr produces a typical austempered ductile iron microstructure consisting of free bainitic ferrite and a stable, highly carbon enriched retained austenite. The maximum value of impact energy (133 J) corresponds to the maximum volume fraction of retained austenite (40 vol%) which was reached after 2,5hr. The whole range of austempering time at 400^{o}C is distinguished by the presence of blocky austenite in which martensite was formed during subsequent cooling to the room temperature. During austempering at 400^{o}C yield strength, tensile strength and ductility are twice as lower than at 320^{o}C. The low values of tensile properties coincide with the appearance of martensite in the microstructure [29]

CHAPTER 4

EXPERIMENTAL PROCEDURE

4.1 **EXPERIMENTAL PROCEDURE**

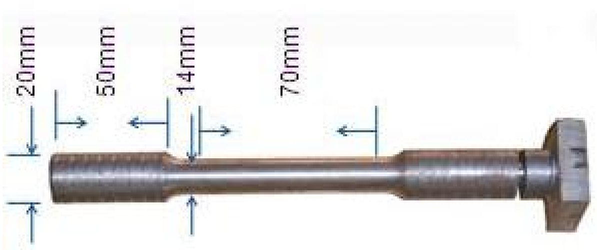
Two different grades of nodular iron samples were used in the present investigation which was produced in a commercial foundry. The major difference between these two grades are copper i.e one grade contains copper (0.56 wt %) and another without copper. The final chemistry of the two grades of nodular iron samples are listed below.

Table 4.1: Chemical composition of the nodular iron (wt %)

Sample	C	Si	Mn	S	P	Cr	Ni	Mg	Cu
N1	3.67	2.32	0.22	0.018	0.029	0.02	0.01	0.048	0.002
N2	3.65	2.28	0.23	0.016	0.032	0.02	0.01	0.052	0.56

4.2 Test Specimen Preparation:

For different tests (Tensile, hardness and metallography), the solid Y block (as per ASTM A 397) of ductile iron was cut to thickness of 20-25 mm using power hacksaw. Then the samples were machined in a lathe machine to prepare exact dimension for tensile test (14 mm dia and 70 mm gauge length) and also for hardness (10x10x55 mm) as per EN1563 specification.



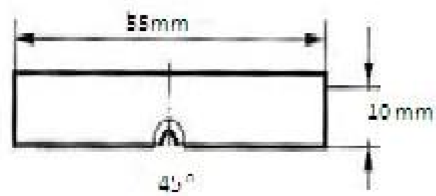


Fig4.2.1. Tensile test specimen after lathe machining

Fig.4.2.2 V-notched charpy impact test specimen

4.3 Heat Treatment (Austenitizing):

Before starting heat treatment, the temperature of the muffle furnace and salt bath was calibrated properly in order to avoid experimental error. 12 nos of samples of each grade (N1 & N2) were austenized to 900^0C in muffle furnace for one hour so that the entire part of the casting got converted to austenite.

4.4 Quenching in a salt Bath (Austempering):

The austenitised specimens were transferred to a salt bath maintained at 4 different temperatures (200^0C, 300^0C, 350^0C and 400^0C). Three specimens at a time were austenitised and after austenitising them, they were immediately transferred to the salt bath. After a time interval of 60 minutes one of the specimens was taken out from the salt bath and water cooled. After next 30 minutes the other specimen was water cooled and after 30 minutes the last specimen was water cooled. This process was carried out for both hardness testing and tensile testing specimens and for both the grades (N1 and N2)

4.5 Specimens for Metallographic analysis

Samples for metallographic analysais were taken from the fracture surface of the tensile speciem. Samples were ground and polished in emery paper of different grits size. Mirror polished samples were made by polishing with cloth and dimond paste. All the mirror polished specimens were etched with 2 % nital solution and then SEM analysis was performed for all the etched samples.

4.6 Hardness Measurement

The heat treated samples were polished in emery papers of different grits for hardness measurement. Rockwell Hardness test was carried out at room temperature to measure the hardness of the nodular iron specimens in A scale. The load was applied through the diamond indenter for 10 seconds during testing of all the treated and untreated samples.

Fig4.6. showing hardness measurement

The shape of the indentation is shown in the figure. Five measurements for each sample were taken from one point to other through the centr al line of the casting pecimen and averaged to get final hardness results. A load of 90 kg was applied to the specimen for 10 seconds. Then the depth of indentation was recorded by a programme installed in the computer of arbitrary hardness numbers. Then these values were converted to in terms of required hardness numbers (as Brielle‟s or Vickers hardness numbers).

CHAPTER 5

RESULTS & DISCUSSIONS

5.1 RESULTS AND DISCUSSIONS

In the present investigation, all the parameters viz austempering time and temperature with the effect of alloying element has been studied. The mechanical properties, metallography and hardness measurement were performed for all the heat treated samples. The obtained data has been correlated with standard results. The results are discussed hereunder.

5.1.1 The Tensile Properties

The tensile properties of both the grades (N1 & N2) are given in the following table

Table 5.1.1. Mechanical properties of ADI (for grade N1, without copper)

Austempering Temp (^{0}C).	Time (min)	UTS (MPa)	0.2% PS (MPa)	Elongation (%)	Hardness (R_A)
200	60	1162	977	2.60	88
	90	1148	962	2.84	82
	120	1136	943	2.94	74
300	60	992	812	4.3	78
	90	966	760	4.9	74
	120	978	790	4.8	72
350	60	730	560	6.2	66
	90	880	670	6.8	72
	120	850	642	7.4	69
400	60	620	436	5.7	46
	90	760	526	5.9	56
	120	736	480	5.4	53

Table5.1.2. Mechanical Properties of ADI (for grade N2, with Copper)

Austempering Temp (^{0}C).	Time (min)	UTS (MPa)	0.2% PS (MPa)	Elongation (%)	Hardness (R_A)
200	60	1210	1040	2.2	88
	90	1192	992	2.5	84
	120	1178	1002	2.4	80
300	60	1052	875	3.6	78
	90	1082	888	3.7	75
	120	1072	862	3.9	73
350	60	960	782	6.1	75
	90	951	764	5.9	72
	120	942	732	5.8	68
400	60	702	515	5.4	60
	90	810	620	5.7	67
	120	758	586	5.6	64

5.2 Effect of Austempering temperature and time on hardness

The hardness values of the samples with Cu (N2) get increased as compared to the specimens without Cu (N1) in ADI by 6 to 10 Rockwell Hardness unit in A scale for all the austempering process adopted in the present study.

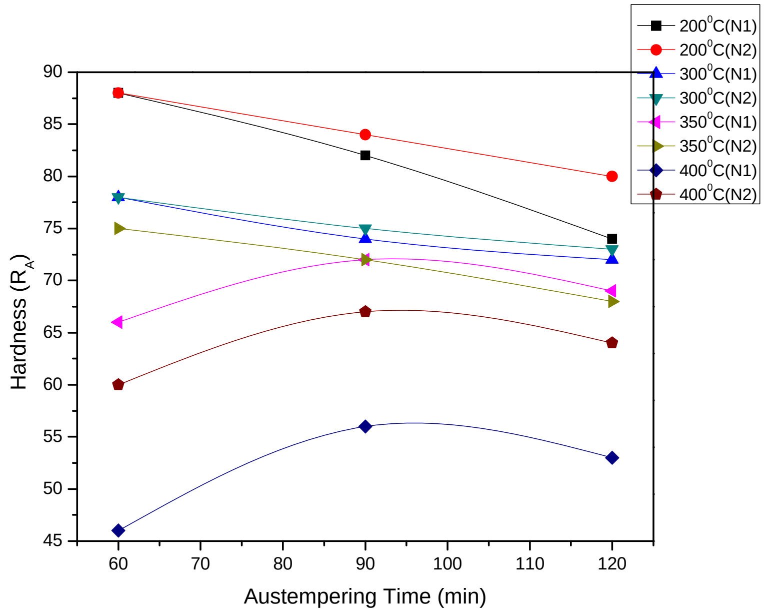


Fig 5.2.1. Effect of hardness on austempering time and temperature

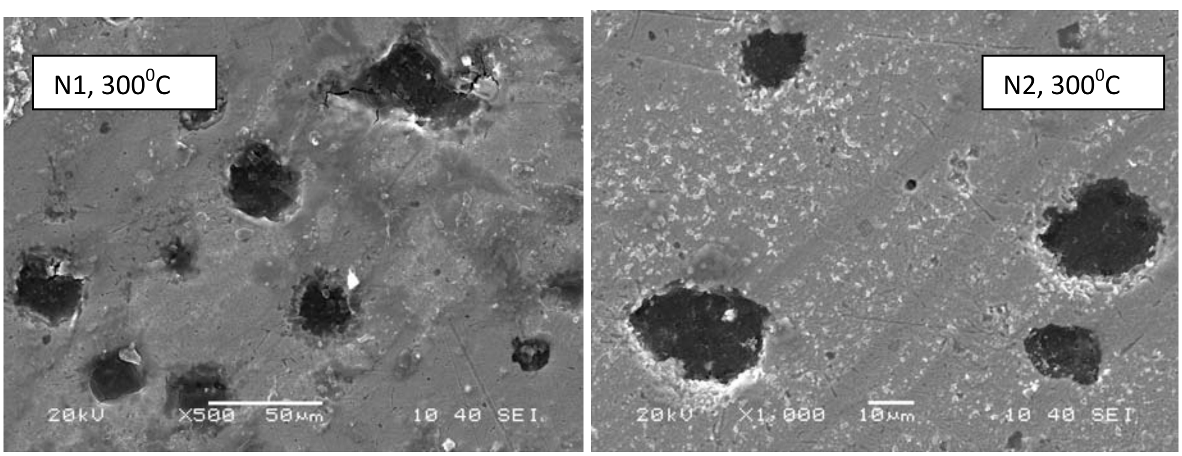


Fig 5.2.2. SEM micrographs of N1 and N2 austempered at 300^{0}C for 60 minutes

This enhancement in hardness over the specimen without Cu may be due to the presence of large amount of pearlite in the matrix of the specimen alloyed with Cu [40]. Hardness is increasing up to one hour austempering time, from one hour to one and half an hour it starts decreasing and from one and half an hour to two hours sometimes increasing and sometimes increasing. In general, it may be it is observed that hardness isincreasing from half an hour to one hour and for one hour, one and half an hour and two hours

5.3 Effect of Austempering temperature and time on Tensile Strength

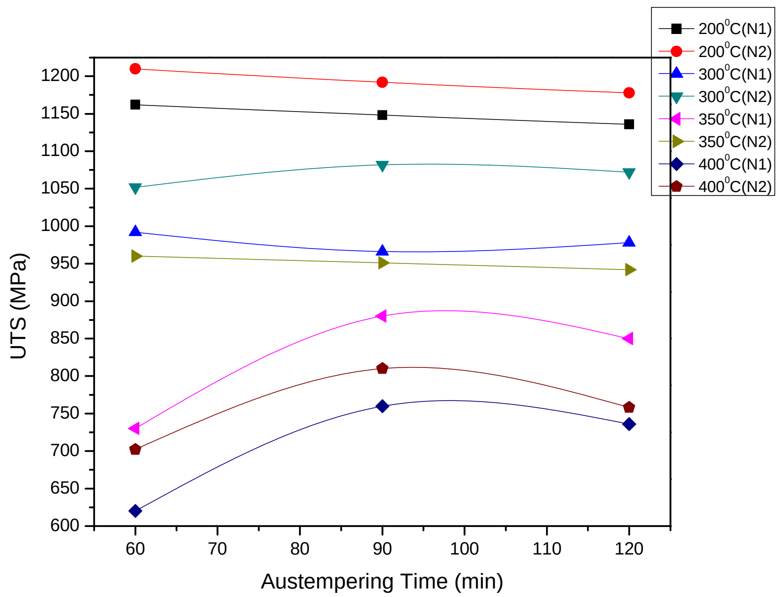


Fig.5.3.1 Effect of austempering temperature and time on UTS.

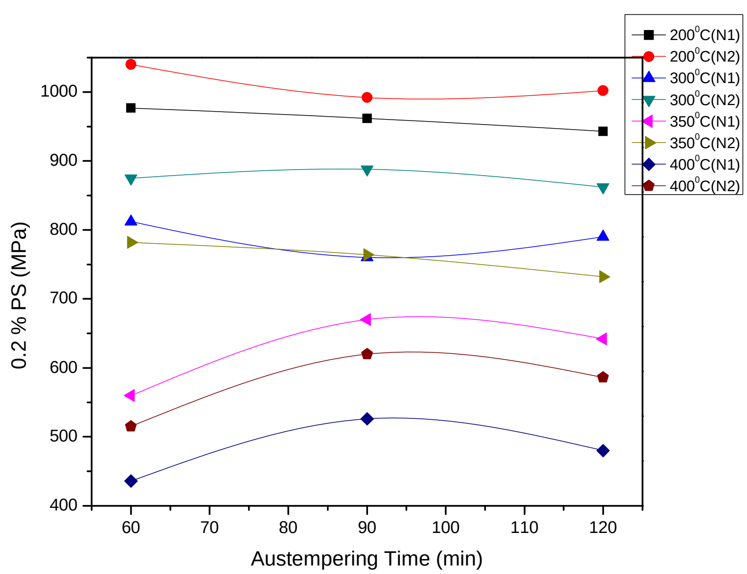


Fig. 5.3.2 Effect of austempering temperature and time on Yield Strength.

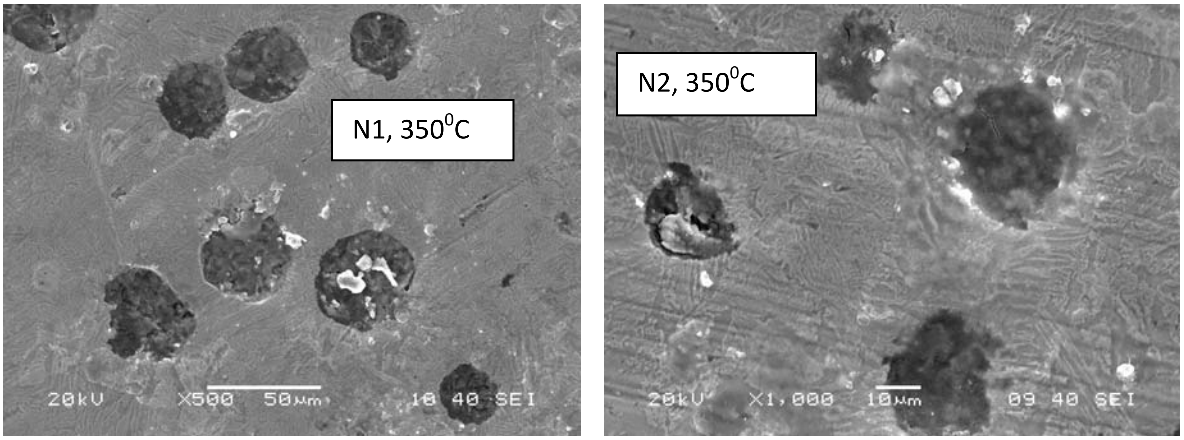


Fig. 5.3.3 SEM micrographs of N1 and N2 austempered at 350^{0}C for 60 minutes

It is observed that tensile strength and yield strength of the samples with Cu (N2) gets increased as compared to the samples without Cu (N1), but Copper decreases ductility of ADI by some nominal value. As Cu is a pearlite promoter and the matrix of the ADI with Cu as the alloying element contains much large amount of pearlite but that without Cu contains large amount of ferrite. Tensile strength is decreasing with respect to the austempering temperature. i.e with increasing austmpering temperature tensile strength is decresing in both grades.

The hardness values, tensile strength and yield strength of Grade N2 are increased as compared to grade N1. During isothermal transformation both stage I and stage II reaction procees depending on both austempering time and temperature. The bainitic transformation in the austempered ductile iron occurs in a two stage phase transformation reaction. In the initial stage, primary austenite (Υ) decomposed to ferrite (α) and high carbon-enriched stable austenite (Υ_{HC}). This transformation is commonly known as the stage I reaction [42]. Mathematically it is written as,

Stage I: $\Upsilon \rightarrow \alpha + \Upsilon_{HC}$

If the specimen is hold for a longer austempering temperature, then stage II reaction proceeds, where high-carbon austenite further decomposed into ferrite and carbide [42].

Stage II: $\Upsilon_{HC} \rightarrow \alpha +$ Carbide

Stage II reaction is not favorable for property enhancement of nodular iron, since it causes the embrittlement and the mechanical properties of ADI decreases. The c ε carbide is brittle which acts as a detrimental phase constituent, hence stage II reaction is always avoided in austempering process.

5.4 Effect of Austempering temperature and time on Elongation

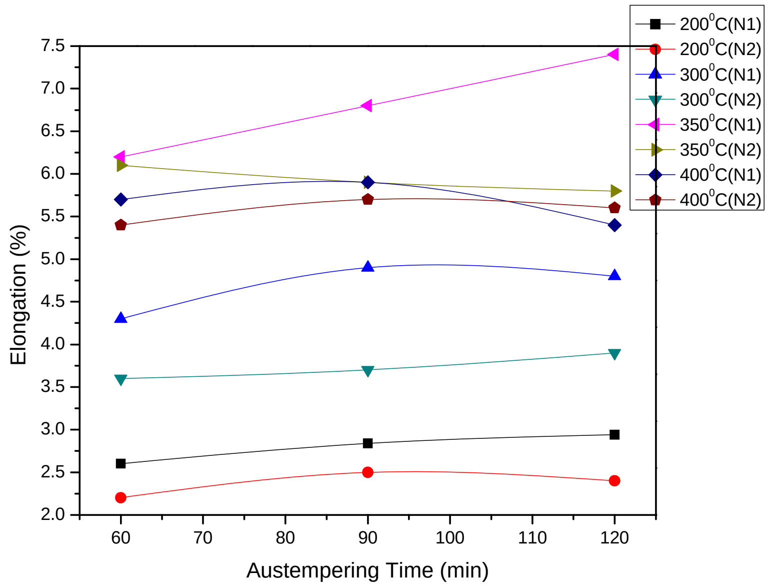


Fig.5.4.1 Effect of Austempering temperature and time on Elongation

The lower elongation values for shorter austempering times may be attributed to the presence of martensite in the matrix of the bainitic structure. But as the austempering time increases, the amount of retained austenite increases as a result the elongation increases. This value reaches a maximum until and unless the completion of stage I reaction is completed and with the starting of stage II reaction, the ductility decreases leading to decrease in retained austenite.

For smaller austempering times, as the stage I reaction proceeds, the amount of bainitic ferrite and high carbon austenite (γ_{HC}) gradually increases. But retained austenite is too less to make all the retained austenite stable at room temperature and some transformation of martensite is occured. With the increase in austempering time, the amount of retained austenite and bainitic ferrite increases till the bainitic transformation is completed, the tensile strength and yield strength and hardness is increased. If austempering process is continued for longer duration, stage II reaction starts and retained austenite decomposes to bainitic ferrite and carbide which results in decrease of hardness, tensile strength and yield strength after reaching a maximum value.

The increase in yield strength (YS) and tensile strength (UTS) for grade N2 (with Cu) in comparison to grade N1 (without Cu), for different austempering times(60, 90 and 120 minutes) initially increases rapidly with temperature, reaches a maximum value and then becomes constant, further increase in time and temperature, the vaues are decreasing. It is observed that, above 60 minutes austempering times, the rate of increase in tensile strength initially increases with temperature and reaches some peak value at 350˚C and then starts decreasing with further increase in austempering temperature. Due to the presence of coarser bainitic ferritic structure at higher austempering temperatures, the decreasing in strength may be more pronounced than the effect of pearlite matrix in in N2 grade. It is observed that, at higher austempering time and temperature, the strength (YS and UTS) decreases for N2 grade specimens than N1 grade specimens.

5.5 X-Ray Diffraction Analysis

The XRD pattern for ADI, which were austempered at 250^0C and 350^0C for 60 minutes and 120 minutes are listed below.

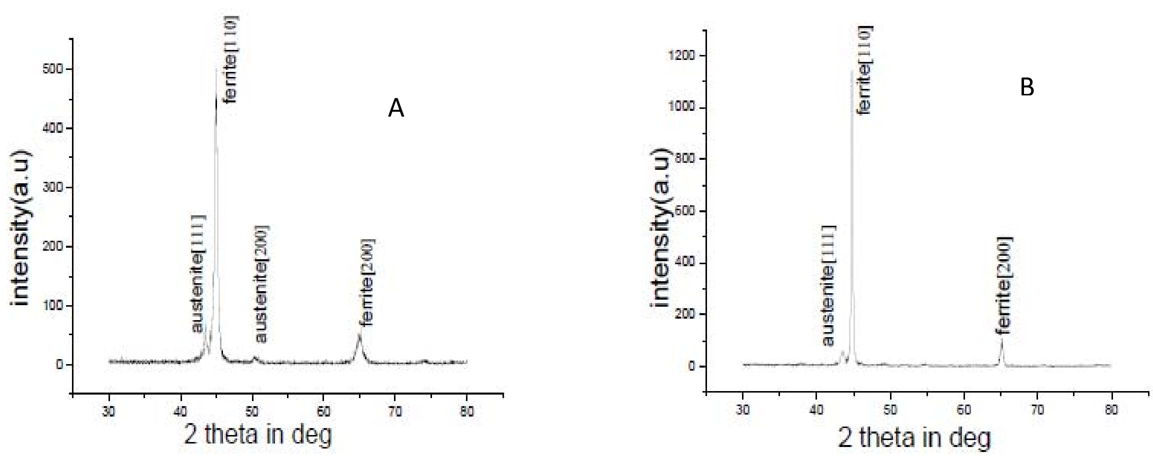


Fig.5.5.1 XRD pattern of ADI austempered at 300^0C for (A) 60 minutes and (B) for 120 minutes for grade N1.

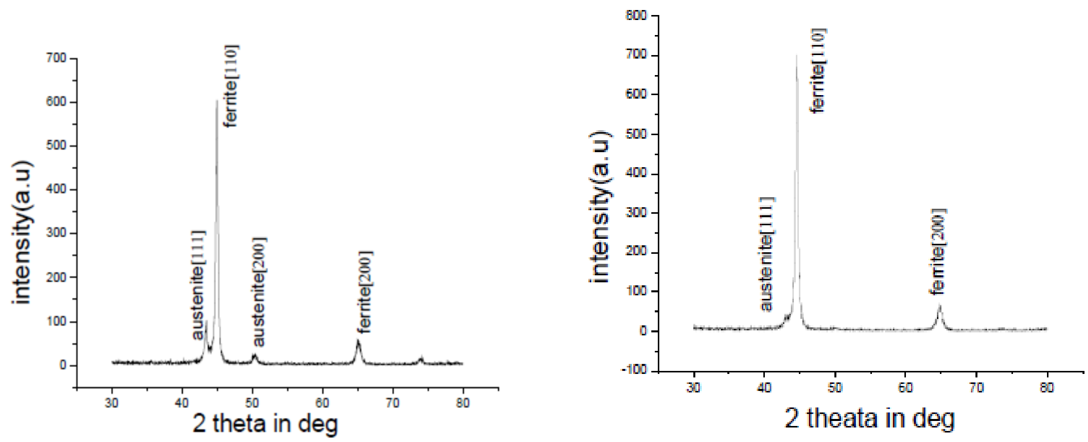


Fig.5.5.2 XRD pattern of ADI austempered at 350^0C for (A) 60 minutes and (B) for 120 minutes for grade N2.

It is observed that in both the figures 5.5.1 and 5.5.2, the austenite (111) and ferrite (110) lines are common and easily identified. But in figure 5.5.2, both ferrite (110) and austenite (111) lines are more prominent and increases with increase in austempering temperatures. The maximum intensity of the austenite (111) line increases with increasing temperature but ferrite (110) line increases with increasing austempering time and decreases with increasing temperature. It may be observed that both the austenite (111) and ferrite (110) lines are identified nearly in all cases. The maximum intensity of the austenite (111) line is increasing with increasing temperature but ferrite (110) line is increasing with increasing austempering time and decreasing with austempering temperature. Hence austempering calls for very precise control of process variables (austempering time and temperature).

CHAPTER 6

CONCLUSIONS

6.1 CONCLUSIONS

The following conclusions may be made from the present investigation.

The effect of alloying element (Cu) on the mechanical properties of nodular iron austempered at four different temperatures (200^0C, 300^0C, 350^0C and 400^0C) with varying austempering time has been investigated in the present investigation. The following conclusions are made:

1. Alloying element (Cu) improves the mechanical properties (UTS, YS and Hardness) of spheroidal graphite iron after austempering.The increasing is constant with austempering time but with increasing austempering temperature it initially increases and then gradually becomes constant.

2. The ductility of ADI also initially increases with austempering time up to a certain value and then it starts decreasing with further increase in time while maintaining austempering temperature constant.Hardness,tensile strength and yield strength of ADI decreases continuously with austempering temperature.

3. The ductility of ADI initially increases with austempering temperature and then after reaching some maximum value at around 350^oC, it starts decreasing with further rise in temperature.

4. Presence of copper in the ADI reduces ductility in the present study.

5. The hardness, tensile strength and yield strength of ADI initially increases with austempering time and then after reaching certain maximum value they decreases.

6.2 FUTURE SCOPE OF WORK

Many research works are being carried out to increase in mechanical property to meet Quality Index established for ductile iron castings. Different alloy like Mo, Ni may be added during melting in different wt% to properly characterize both mechanical properties as well as graphite morphology of Austempered Ductile Iron to meet standard of expection as required to establish a better structure-property correlation. DSC analysis should be carried out at every austempering time and temperature to justify proper transformations in different conditions in the matrix during austempering process and on set of stage I and Stage II reaction. XRD analysis should be carried out in the diffraction angle range from 60degree to 130degree for clear understanding of the lattice, lattice plane and different phases. Austempering time and temperature may be extended further to observe the change in mechanical behavior and change in graphite morphology.

CHAPTER 7

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