EFFECT OF PROCESSING PARAMETERS ON PROPERTIES OF ALLOYED AUSTEMPERED DUCTILE IRON

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

Master of Technology (Research)

In

Metallurgical & Materials Engineering

By

Amar Kumar Das

National Institute of Technology, Rourkela.
Rouekela-769 008, Odisha, India
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(Roll No:608MM302)

Under the supervision of

Dr. SudiptaSen

**Department of Metallurgical &Materials Engineering
National Institute of Technology, Rourkela.
December-2012**

Dedicated to

My Father

Late BabajiCharan Das

Department of Metallurgical & Materials Engineering

National Institute of Technology Rourkela

Rourkela-769 008, Orissa, India

CERTIFICATE

This is to certify that, the work embodied in this project report entitled **"*Effect of processing parameters on properties of alloyed austempered ductile iron*"** by **Mr.Amar Kumar Das** is an authentic record of work carried out by him under my supervision and guidance for partial fulfilment of the requirements for the degree of Master of Technology (Research) 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.

Date:

Dr. SudiptaSen

Associate Professor

Department of Metallurgical & Materials Engineering

National Institute of Technology, Rourkela.

ACKNOWLEDGEMENT

Date: Amar Kumar Das

Contents

Chapter-1

Introduction

Chapter-2

Literature review

Chapter-3

Chapter-4

Chapter-5

Chapter-6

ABSTRACT

Ever since its discovery in 1948, the use of ductile iron is increasing continuously, this is due to the combination of its various excellent mechanical properties of the material. Extensive research is being carried out to develop even better properties. Austempered ductile iron is the most recent development in the area of ductile iron or S.G. iron. This is formed by an isothermal heat treatment of the ductile iron. The newly developed austempered ductile iron is now replacing steel in many fields so it is becoming very important to study various aspects of this material. In the present work the effect of Copper and Nickel as alloying element along with the process variables (austempering temperature and austempering time) on the properties (Hardness, Tensile strength and Elongation) and microstructure of ductile iron has been studied. With increasing austempering time hardness, tensile strength and elongation are increasing but with increasing austempering temperature hardness and tensile strength are decreasing and elongation increasing. Austempered ductile iron with alloying element (Cu or Ni) is showing some higher strength, hardness and lower elongation than the unalloyed austempered ductile iron. In microstructure ferrite is increasing with increasing austempering time and austenite is increasing with increasing austempering temperature in all the Cu alloyed, Ni alloyed and unalloyed grades.

Key words: S.G. Iron, Austempering, austempered ductile iron, austempering time and temperature, austenite and ferrite

LIST OF FIGURES

LIST OF TABLES

Chapter 1

Introduction

CHAPTER 1	**Introduction**

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

A ductile iron which subjected to a special 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 essential for austempered ductile iron.

Ductile Cast Iron undergoes a remarkable transformation when subjected to the austempering heat process. The resulting 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 capability superior to many traditional, high performance, ferrous and aluminum alloys. Ausferrite exhibits twice the strength for a given level of ductility compared to the pearlitic, ferritic or martensitic structures formed by conventional heat treatments.

The mechanical properties of the austempered ductile iron depend on the ausferrite microstructure. The austempered matrix is responsible for significantly better tensile strength to ductility ratio than is possible with 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 alloying elements. Alloy additions may be made to austempered ductile iron with a view to control the matrix structure. This mode of solidification is obtained by adding a very small, but specific amount of Mg or Ce or both to molten metal of a proper composition.

The base iron is severely restricted in the allowable contents of certain minor elements that can interfere with the graphite spheroid formation. The added Mg reacts with S and O in the molten

iron & changes the way the graphite is formed. Austempered ductile iron (ADI) is considered to be an important engineering material because of its attractive properties such as good ductility at high strength, good wear resistance and fatigue strength and fracture toughness. Because of these combinations of properties, ADI is now used extensively in many structural applications in automotive industry, defense and earth moving machineries. The optimum mechanical properties of ADI i.e., the adequate combination of strength, toughness, fatigue strength, and wear resistance could be achieved if the microstructure consists of retained carbon-enriched stable austenite (enables ductility), together with one of two bainitic morphologies, namely, carbide-free bainitic ferrite or bainitic ferrite, in which carbides are distributed in the ferrite (affects strength)[3,4].

The mechanical properties of ADI depend on the microstructure, which in turn depends on the austempering variables, i.e. austempering temperature and the time of holding. In conventional ductile iron the mechanical properties can be attributed to the pearlite and the ferrite present in the matrix but the superiority in the mechanical properties of the ADI are due to the acicular ferrite and carbon enriched stabilized austenite present in the matrix[4]. The proportion in which these two phases are present depends on the austempering variables.

The base iron chemistry and the alloy additions in ductile iron, plays important role in ADI technology. Most of the ADI needs to be alloyed for satisfactory austemperability and subsequent improvement in properties. Now-a-days many researches for ADI are done to study the effect of the alloying elements on the microstructure, mechanical properties. As an alloying element, copper widens the austenite zone of the phase diagram increasing the transformation rate during austenitising process and the carbon content in the matrix. On the other side, during the austempering process, copper may subdue carbide formation[5].

In present research work, the effect of copper alloying as well as the effect of heat treatment parameters like austempering time and austempering temperature on microstructure and properties of the ductile iron were studied.

Chapter 2

Literature review

Cast irons are basically alloys of iron and carbon like steels but contain greater amount of carbon. Cast irons contain 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 of cast iron is very low. They melt readily and can be cast into complicated 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. White cast iron, malleable cast iron, gray cast iron, nodular cast iron and alloyed cast iron are different type of cast irons [6].

2.1. Ductile iron

If coke had not been used for melting iron and if high purity ores had been used then ductile iron would have been accepted as normal form of iron [7].Ductile iron is also known as nodular iron, spheroidal graphite iron and spherulitic iron in which graphite is present in tiny balls or spheroids[6]. 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% [7]. Ductile iron, also referred to as nodular or spheroidal graphite cast iron constitutes a family of cast irons in which the graphite is present in a nodular or spheroidal form. Ductile iron derives its name from the fact that, in the as-cast form, it exhibits measurable ductility. By contrast, neither white cast iron nor grey cast iron exhibits significant ductility in a standard tensile specimen.

2.1.1. Back ground

The first announcement of SG cast iron was made on 7th May, 1948 at the American Foundry men's association meeting in Philadelphia, Pennsylvania.This was culmination of an exciting period of research and initiated an era of one of the most dramatic commercial developments in the metals world.

The metallurgists then began seriously to study the effects of variations in composition, melting procedures, solidification characteristics, cooling rates and many other parameters. Effects were being made to correlate strength to size,amount,shape,distribution of graphite's& methods of influencing these factors were being developed.However,the technical literature at that time was completely silent regards to i) a cast iron having it's graphite in the spheroidal form in the as cast condition or ii) a high carbon of any type exhibiting ductility in the as cast condition.

One of the materials to be born in this era and which was being promoted in the 1930's was an abrasion resistant white cast iron with high hardness which results from a martensite-carbide matrix promoted by Ni & Cr contents nominally of 4.5 & 1.5 % respectively. These materials are still produced in large quantities all over the world for grinding mill balls,plates,rolls and many applications requiring outstanding abrasion resistance. It is well known in Australia and very likely will enjoy a sizable growth in view of the huge mining potential.After 2nd world war, Cr appeared to be one of the elements that would become scarce and without it;white cast would be of lessercarbide,considerably softer and hence lacking in the desired abrasion resistance.

To meet the eventuality, research laboratories all over the world seek a substitute element of Cr as a carbide former in martensite white cast iron.Necessarily,the element has to satisfy all the three conditions,i.e., be plentiful, non-critical to the war effort and be required in small amount. All the metallic and semi metallic elements which were known to combine chemically with carbon to form carbide were tested. Among these was Mg. Further, it was believed by the investigators that the solubility of Mg in ferrous materials was exceedingly low.The main purpose of addition of Mg was deoxidation, evidently with no desire or hope of retaining in the iron. The addition of Mg to the base iron exhibited unusual toughness by resisting fracture where

as other broke in usual brittle manner. It was later learnt an analytical method to determine Mg in cast iron. It is known that Mg is retained in iron & in instances to more than 1%.

The next step, obviously to investigate the effect of Mg on plain grey iron cast iron and such a research programme was started early in 1943.The grey cast iron was treated with various amount of Mg added as 80% Ni-20% Mg alloy up to a minimum of 0.3%. An examination of microstructure showed that refinement of flake graphite hadoccurred.The obvious next step was larger addition of Mg.There was excitement in the laboratory when the heats were tested, for the results lead to the realization that it was not merely an improvement in cast iron that had been achieved,but rather creation of a completely new product.The tensile strength has increased to unexpected level. An immediate examination under microscope revealed that the graphite was not present as flake but as well as dispersed spheroids.With a small, but effective amount of Mg produced high strength spheroidal graphite cast iron as well with good mechanical properties.

Ductile cast irons represent a triumph of 20[th]century metallurgical research. These ironswere developed independently in approximately1948 at the International Nickel Company(INCO) in the United States and at the BritishCast Iron Research Association (BCIRA) inEngland. Both groups discovered that by keeping the sulfur and phosphorus levels low andadding very small amounts of a key chemicalelement, the shape of the graphite could bechanged from the interconnected flakes of grayirons into isolated spheres (usually called spheroids) of graphite. The INCO team showed that the effect was produced by the addition of only 0.02 to0.1% Mg, and the BCIRA team by the additionof only 0.02 to 0.04% Ce (the rare earth metalof atomic number 58)[8].

2.1.2 Birth of Ductile Iron

In spite of the progress achieved during the first half of 20th century in the development of grey and malleable irons, foundry men continued to search for the ideal cast iron-an as-cast "grey iron" with mechanical properties equal or superior to malleable iron. J.W.Bolton, speaking at the 1943 convention of the American Foundry men's Society (AFS), made the following statements.

"Your indulgence is requested to permit the posing of one question. Will real control of graphite shape is realized in grey iron? Visualize a material, possessing (as-cast) graphite flakes or groupings 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 laddle addition of magnesium (as a copper magnesium alloy) to cast iron and justified Bolton's optimism-the solidified castings contained not flakes, but nearly perfect spheres of graphite. Ductile Iron was born!

Five years later, at the 1948 AFS Convention, HentonMorrogh of the British Cast Iron Research Association announced the successful production of spherical graphite in hypereutectic gray iron by the addition of small amounts of Cerium.

At the time of Morrogh's presentation, the International Nickel Company revealed their development, starting with Milli's 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 Keith D. Millis, Albert P.Gegnebinand 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.

The US transport industry faced three major challenges: reduce emission, improve fuel economy and lower cost. One method of improving fuel economy is to reduce vehicle weight. In 1970's, the automotive industry reduced vehicle weight by reducing the thickness of the steel sheet (driving the development of high-strength low- alloy steels and corrosion resistant coatings). In the 1980's and the early 1990's, vehicle weight was further reduced by substituting aluminum for cast iron and steel (primarily in cylinder heads, engine blocks and wheels). Currently the substitution of aluminum for cast iron and steel, and magnesium is continuing. The use of aluminum, however, results in higher vehicle costs, which are passed on to the consumer. To provide the transport industry with a means of weight reduction at little or no cost penalty, the cast iron and Steel industries have undertaken major product improvement programs e.g. thin wall iron casting technology and light weight steel body technology. Recent research (Javaid, 1999; Javaid, 2000; Labreccque, 2000) has shown the feasibility of producing thin-wall iron castings. Commercially viable, light weight cast iron technology is being developed by TWIG

(Thin-wall Iron Group) through a co-operative program with major US foundry companies, foundry suppliers, the Big three automakers, the University of Alabama, and U.S. Department of Energy Albany Research center. TWIG has launched programs specifically focused on control of microstructure, solidification modeling, process variability, and dimensional capability in thin section castings, generation of useful mechanical data. The worldwide growth of ductile production from 1950 to 200 is given in figure 2.1.
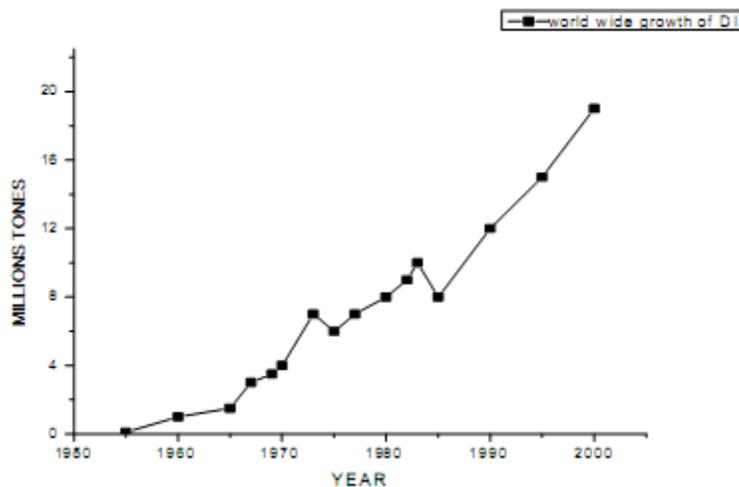
Fig. 2.1 Worldwide growth of ductile iron production, 1950-2000, BTM Consult, March-2000.

2.1.3 Modern Trends

During the first 20 years of SG iron production; there have been many significant changes in foundry equipment, materials &practices. The development & growth of many of these related directly to improve the process of producing SG iron and now the production of good quality SG iron is a routine affair. All are more familiar with these changes which include the development of basic cupola, the water cooled cupola, the commercial development of shell molding, alloys and devices for treating the iron, to a new fame. In Europe, induction furnace melting gained popularity because of the more precise control it afforded for composition and temperature plus the fact that a wide variety of charge materials could be used. In the early 1960s interest in electric arc furnace melting spread to other parts of the world. It facilitated a finer degree of quality control in meeting the various requirments.

Designer Engineers can now optimize casting shape and performance with increased speed and confidence. Recent development in CAD/CAM, solid modeling and finite element analysis (FEA) techniques permits highly accurate analysis of stress distributions and component deflections under simulated operating conditions, In addition to enhancing functional design, the analytical capabilities of CAD/CAM have enabled foundry engineers to maximum casting integrity and reduce production costs through the optimization of solidification behavior.

Castings offer cost advantages over fabrications and forgings over a wide range of production rates, component size and design complexity. The mechanization and automation of castings process have substantially reduced the cost of high volume castings, while new and innovative techniques such as the use of Styrofoam patterns and CAD/CAM pattern production have dramatically reduced both development times and costs for prototype and short-run castings. As confidence in FEA techniques increases, the importance of prototype, often in the form of fabrications which "compromise" the final design, will decrease and more new components will go directly from the design stage to the production castings.

Nowadays the automotive, wind power and agricultural implements industries are major users of ductile iron castings. Automotive castings requirements represent approximately 55 percent of the total worldwide ductile iron casting production. The rapid growth of ductile iron industries and the high annual utilization of ductile iron castings are testimonials to the out standings mechanical properties, quality and economics of ductile iron castings. The fact that ductile iron castings are used for such critical automotive applications as crankshafts, front wheel spindle supports, and connecting rods is a further testimonial to the high reliability and process economics associated with ductile iron castings.

2.1.4 Its Development & Future

The year 1959 marked the start of rapid growth in the demand for casting and the ensuing annual increases in production were almost phenomenal. Various attempts were made to determine the industrial distribution of spheroidal graphite iron castings. Difficulties arise from the fact that the

utilization of the materials varies in different parts of the world. For example, pipes account for about 26% of the production in US, in Japan on the other hand, it accounts for about 70% of the production. In US, three industries consume the major share of the production. Automotive applications take about 40%, pipes 26% and agricultural implements something in excess of 5%. This is probably similar to the situation existing in the rest of the world. However, someone would be very hard pressed to find an industry which did not make use of some spheroidal graphite cast iron, either directly or indirectly. The first stainless steel was patented in the year 1914, but there were no production figures available for years prior to 1929. It is evident thatafter 16 years, the patent was issued. The production of stainless steel was low as compared to the production of SG cast iron was patented. In fact, it took stainless steel 47 years to reach the level that SG cast iron reached in sixteen years.

The advantages of ductile iron which have led to its success are numerous, but they can be summarized easily – versatility and higher performance at lower cost. Other members of the ferrous castings family may have individual properties which might make them the material of choice in some applications, but none have the versatility of ductile iron, which often provides the designer with the best combination of overall properties. This versatility is especially evident in the area of mechanical properties where ductile iron offers the designer the option of choosing high ductility, with grades guaranteeing more than 18% elongation, or high strength with tensile strength exceeding 825Mpa.

2.1.5 Design Flexibility

The design flexibility offered by the casting process far exceeds that of any other process used for the production of engineering components. This flexibility enables the design engineer to match the design of the component of its function. Metal can be placed where it is required to optimize the load carrying capacity of the part, and can be removed from unstressed areas to reduce weight. Changes in cross-section can be streamlined to reduce stress concentrations. The result is that both initial and lifecycle costs are reduced through material and energy conservation and increased component performance.

A recent study by the National Center for Manufacturing Sciences (NCMS) has shown that in certain machine tool applications, the replacement of fabricated structures by Ductile Iron

castings could result in cost savings of 39-50%. Commenting on the NCMS study, Mr. Gary Lunger, president of Erie Press Inc. stated:

"We make huge presses and we have relatively clear specifications for what goes into each press. We have been able to use Ductile Iron as a substitute material primarily for cylinders and other parts at a significant cost saving over cast or fabricated steel". The sudden arrival of SG cast iron on the material science more than 20 years ego provided a cast iron with spectacularly better properties than grey cast iron and better castability than steel. In times, engineers realized that it was not a single material with one set of properties, rather available at will and capable of serving a wide variety of engineering equipment.

A more interesting area for improved ductile iron lies in the possibility of property improvements of sufficient magnitude to permit a redesign that would result in net reduction in cost for a part, increase life of a part to a degree that the alloy cost would be offset or substantially improve operating economy of mechanical equipment through the ability to operate under much more severe conditions.

The ductile iron castings have served the automotive industry well in many applications since its inception. In recent years there has been an increasing trend towards use of castings. The modern V-8 engine, in which castings are now used for each of the major components, is an example of this trend. In any central foundry project to develop a new casting application, there are two design objects: First- develop functional characteristics in the castings which are superior to the parts to be replaced. Second- employ the combination of the parts principle offered by the casting process. The integral ductile iron steering knuckle development met both of the objectives. For the integral ductile iron steering knuckle, the designer has been free to incorporate the requirements of ductile ironas well as combining the casting process.

2.1.6 Production of SG Iron

SG Irons are produced directly by the solidification of amelt 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 produceMgS 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 also be employed to tie up oxygen and sulphur. 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 sulphur 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. The process of G. F. Fisher method for production of ductile iron is given in figure 1.2 [7].
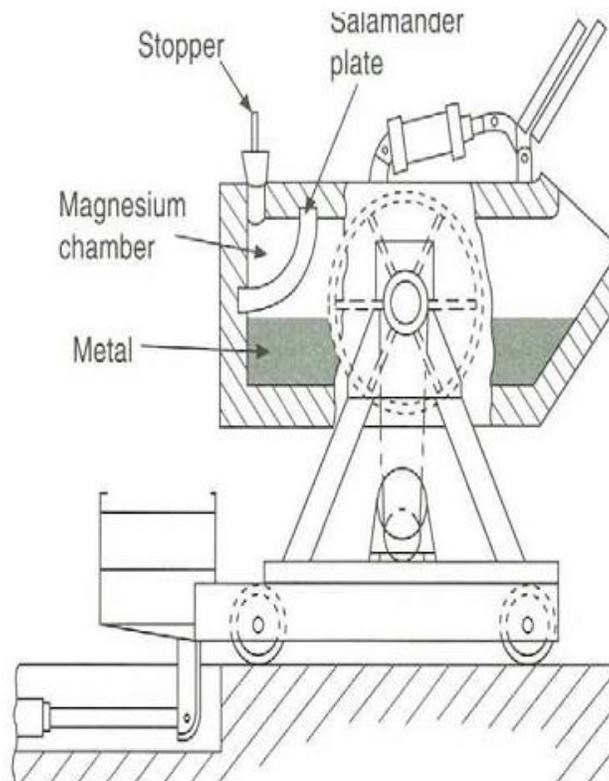
Fig.1.2 G.F. Fisher Method for production of ductile iron [7].

2.1.7 Unique Properties of S.G. Iron

This member of family of cast iron has several interesting properties as:

High strength (In some cases even greater than steel)

Adequate Ductility.

Superior castability (Foundry men friendly)

Excellent machinability (As compared to steel)

Lower density then that of steel

Superior surface lubrication properties

Better damping characteristics (As compared to the steel)

2.1.8 Chemical composition

For common cast iron, the main elements of the chemical composition are carbonand silicon. High carbon content increases the amount of graphite or Fe_3C. Highcarbon and silicon contents increase the graphitization potential of the iron aswell as its castability.The manganese content varies as a function of the desired matrix. Typically, itcan be as low as 0.1% for ferrule irons and as high as 1.2% for pearlitic irons,because manganese is a strong pearlite promoter.From the minor elements, phosphorus and sulfur are the most common and arealways present in the composition. They can be as high as 0.15% for low-qualityiron and are considerably less for high-quality iron, such as ductile iron or compacted graphite iron [9].

The main effect of chemical composition in nodular (ductile) iron is on graphite morphology. Thecarbon equivalent has only a mild influence on the properties and structure ofductile iron, because it affects graphite shape considerably less than in the caseof gray iron. Nevertheless, to prevent excessive shrinkage, high chilling tendency,graphite flotation or a high impact transition temperature, optimum amounts ofcarbon and silicon must be selected. Minor elements can significantly alter thestructure in terms of graphite morphology, chilling tendency, and matrixstructure. Minor elements can promote the spheroidization of graphite or canhave an adverse effect on graphite shape [9].

2.1.9 Structure

The main difference between ductile iron and grey iron is the morphology of graphite particles 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 carbide are dispersed. The following important microstructural components are found in ductile iron [10]. Fig 2.3 shows Mirostructure of ductile iron (a) unethed (b) nital etched.

(a)   (b)
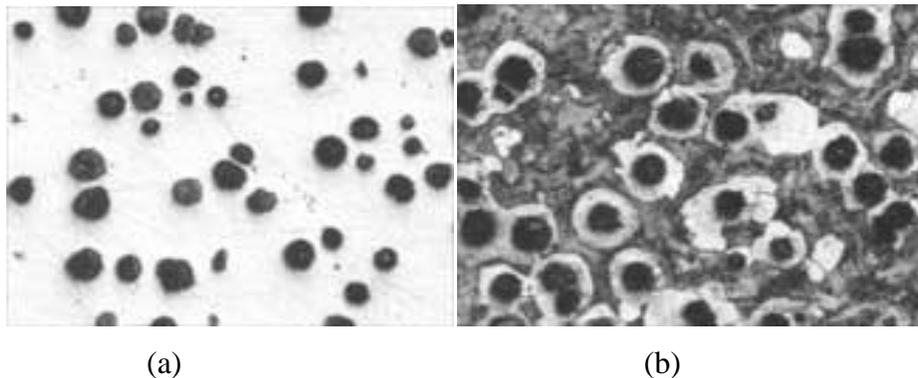
Fig 2.3.Mirostructure of ductile iron (a) unethed (b) nital etched :100X [22].

2.1.9.1. 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 ductile irons. Ductile iron is characterized by having all of its graphite occurs in microscopic spheroids. Although this graphite constitutes about 10% by volume of ductile iron, its compact spherical shape minimizes the effect on mechanical properties [11].

2.1.9.2. 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. The strength properties of ferritic ductile iron are generally

increased by the elements, which go in to the solution. With the exception of carbon, all the elements increase tensile strength and hardness. An example of the extent to which ferrite is affected by solid solution strengthening is illustrated for the elements silicon and nickel [11].

2.1.9.3. 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 [11].

2.1.9.4. Martensite

Martensite is a supersaturated solid solution of carbon in iron produced by rapid cooling. In the un-tempered condition it is very hard and brittle. Martensite is normally "tempered"-heat treated to reduce its carbon content by the precipitation of carbides-to provide a controlled combination of high strength wear resistance and ductility [11].

2.1.9.5. Austenite

Normally a high temperature phase consisting of carbon dissolved in iron, it can exist at room temperature in austenitic and austempered cast iron. In austenitic irons, austenite is stabilized by nickel in the range of 18-36% [31]. In austempered irons, austenite is produced 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 provides ductility and toughness at all temperatures, corrosion resistance and good high temperature properties, especially under thermal cycling conditions. In austempered ductile iron stabilized austenite,volume fractions up to 40% of lower strength grades, improves toughness and ductility and response to surface treatments such as fillet rolling [11].

2.1.9.6. Bainite

Bainite is a mixture of ferrite and carbide, which is produced by alloying or heat treatment [11].

2.1.10 Types of ductile iron

With a high percentage of graphite nodules present in the structure, mechanical properties are determined by the ductile iron matrix. The importance of matrix incontrolling mechanical properties is emphasized by the use of matrix names to designate the following types of Ductile Iron [10, 11].

2.1.10.1. Ferritic Ductile Iron

Graphite spheroids in a matrix of ferrite provide an iron with good ductility and impact resistance and with a tensile and yield strength equivalent to low carbon steel. Ferrite ductile iron can be produced as-cast but may be given an annealing heat treatment to assure maximum ductility and low temperature toughness [10, 11].

2.1.10.2. Ferrito- 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 [10, 11].

2.1.10.3. 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 resistant. 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 also be alloyed/or heat treated to provide the following grades for a wide variety of additional applications [10, 11].

2.1.10.4. 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 [10, 11].

2.1.10.5. Austenitic Ductile Iron

Alloyed to produce an austenitic matrix, this ductile iron offers good corrosion and oxidation resistance, and good strength and dimensional stability at elevated temperatures [10, 11].

2.1.10.6. Austempered Ductile iron (ADI)

ADI, the most recent addition to the ductile iron family, is a sub-group of ductile iron 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 [10, 11].

Austempering is the heat treatment process in which austenite transforms isothermally to lower bainite and thus is used objectively to reduce distortion and cracks. In austempering the steel is heated to the austenitic range and then the steel is quenched in molten salt bath held at a temperature above Ms and the austenite at this temperature is let to transform to lower bainite. The detailed process of transformation is shown in TTT diagram (figure 2.4).
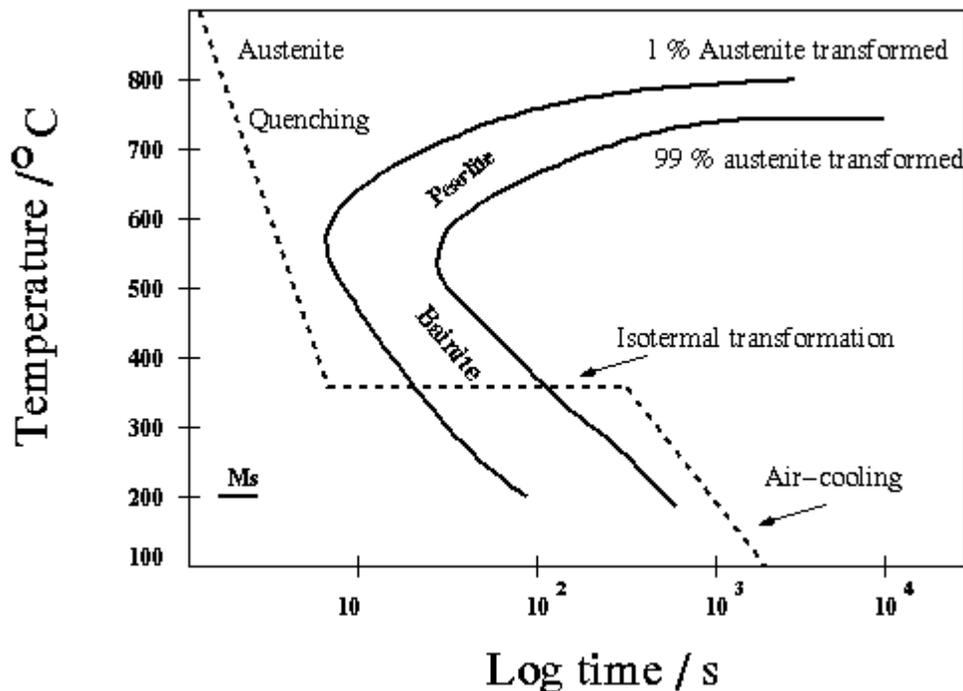
Fig. 2.4 Diagram for austempering superimposed on TTT diagram

The steel to be austempered should have adequate hardenability so as to avoid pearlitic transformation when the steel is quenched from the austenitic range into a heated molten bath maintained at a temperature above Ms. Moreover the bainitic bay should not be long, else bainitic transformation will be incomplete. The major processing advantage of austempering is that is does not require tempering.

Austempering results in enhanced ductility, enhanced toughness, higher hardness and lesser distortion and quench cracks than that observed after tempering of hardened specimen.

Combination of attractive properties such as good ductility at high strength, good wear resistance and fatigue strength and fracture toughness can be obtained for ADI[3]. The desired mechanical properties of ADI i.e., the adequate combination of strength, toughness, fatigue strength and wear resistance could be achieved by varying the austempering variables, i.e. the temperature at which austempering is done and the time of holding.

The attractive properties of ADI are due to the uniqueness in its microstructure which consists of ferrite (α) and high carbon austenite (Υ_{HC}). This is different from the austempered steels where the microstructure consists of ferrite and carbide. The product of austempering reaction in ductile iron is often referred to as ausferrite rather than bainite[3]. The high silicon content of the ductile iron suppresses the precipitation of carbide during austempering reaction and retains substantial amount of stable high carbon austenite (Υ_{HC})[3, 4]. During austempering, the bainitic ferrite forms by rejection of carbon into the residual austenite. As austempering progresses, more of bainitic transformation occurs accompanied by rejection of more carbon into the surrounding austenite resulting in the increase in the amount of austenite and the amount of carbon in the austenite. In earlier stages, the carbon content of austenite is insufficient to make it stable, and therefore, it transforms to martensite. However, at longer times austenite is enriched to the extent that it can become thermally stable to well below room temperature [5].

The bainitic transformation in the austempered ductile iron can be described as a two stage phase transformation reaction. The initial transformation is of primary austenite (Υ) decomposing to

ferrite (α) and high carbon-enriched stable austenite (Υ_{HC}). This transformation is commonly known as the stage I reaction [4].
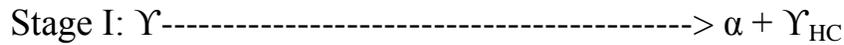
$$\text{Stage I: } \Upsilon \text{---> } \alpha + \Upsilon_{HC}$$

If the casting is held at the austempering temperature for too long time, then a second reaction (stage II) sets in, where high-carbon austenite further decomposes into ferrite and carbide[4].
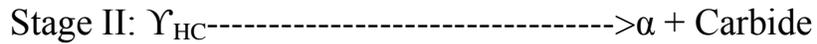
$$\text{Stage II: } \Upsilon_{HC} \text{-------------------------------->} \alpha + \text{Carbide}$$

Stage II reaction is undesirable since it causes the embrittlement of structure and degrades the mechanical properties of ADI [4]. The carbide formed is ε carbide which makes the steel brittle[3]. Since, ε carbide is a detrimental phase constituent, hence this reaction during austempering process must be prevented.

2.1.11 Different grades of ductile iron

Table2.1. Different grades of ductile iron [12].

Grade and heat treatment	Tensile strength (MPa)	Yield strength minimum (MPa)	Percentage of elongation	Brinell hardness	Matrix microstructure
60-40-18 (1)	414	276	18	149-187	Ferrite
65-45-12 (2)	448	310	12	170-207	Ferrite + Pearlite
80-55-06 (3)	552	379	6	197-255	Pearlite + ferrite
100-70-03 (4)	690	483	3	217-269	Pearlite
120-90-02 (5)	828	621	2	240-300	Tempered martensite

2.1.12.Microstructure of different grades of ductile iron

The microstructure of various grades of ductile iron such as: pearlitic ductile iron, Pearlitic-ferritic ductile iron and Ferritic–pearlitic ductile iron is given below figure 2.5 to 2.7. Nodularity is clearly observed in every microstructure.
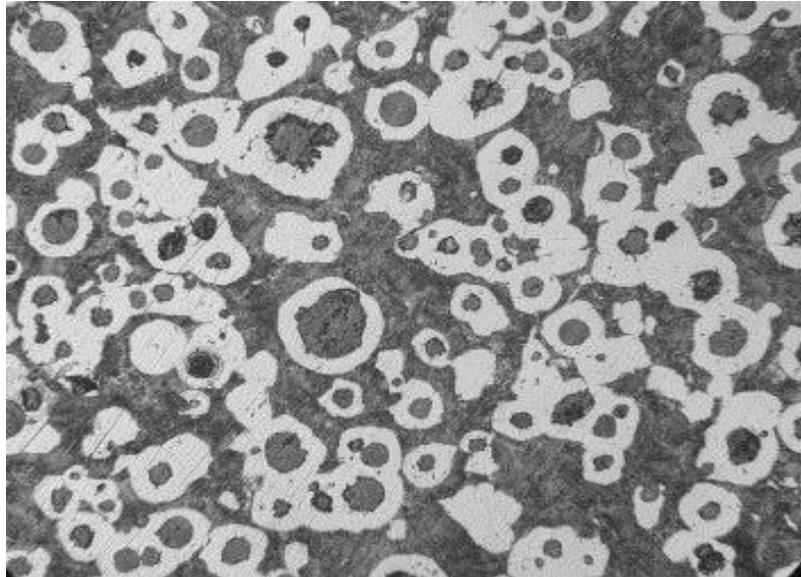
Fig. 2.5 Representative pearlitic ductile iron microstructure [46].
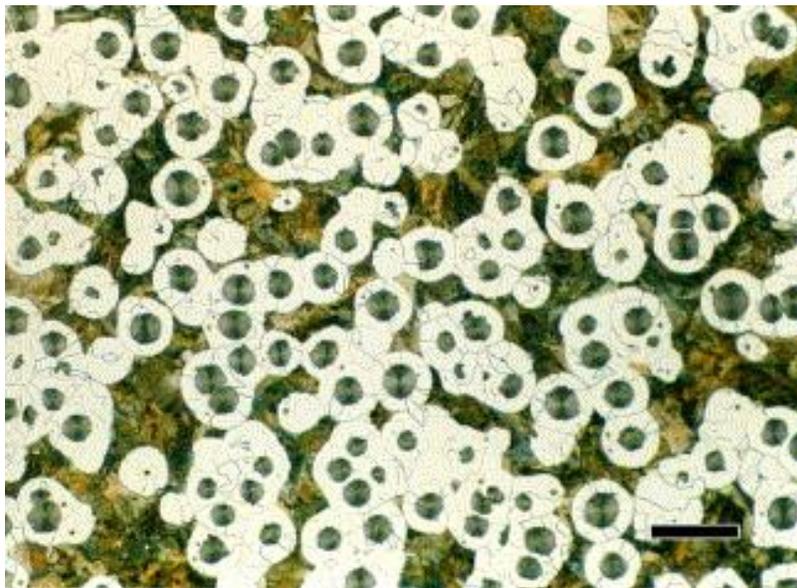
Fig. 2.6Pearlitic-ferritic matrix of a ductile iron after etching with 4% Nital[47].
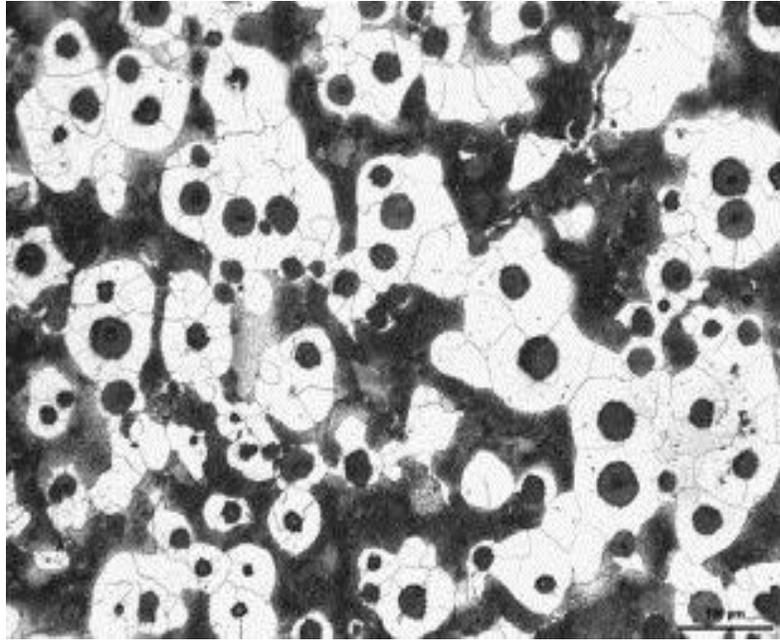
Fig. 2.7Ferritic–pearlitic ductile iron microstructure (Nital 3 %) [48].

2.1.13. 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.

2.1.13.1. Effect of graphite shape

As would be expected from the dramatic differences in mechanical properties between Gray and Ductile 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 influence of modularity on DEM, but also indicates that DEM values obtained 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 intergranular networks of "spiky" or plate-like graphite which result in dramatic reductions in tensile properties [52]. Fig 2.8 shows microstructure of gray and ductile iron.
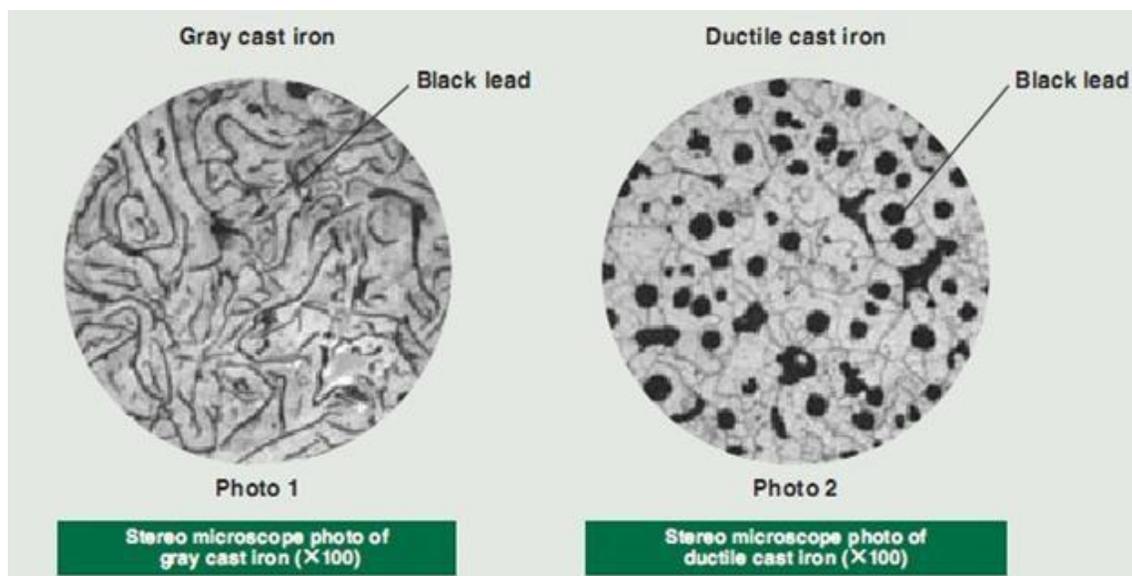
Fig. 2.8 microstructure of gray and ductile iron[53]

The effect 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 Mg-controlled loss of nodularity for the ferritic iron, the pearlitic iron is much more sensitive to reduced nodularity. Second, at low carbide levels typical of good quality Ductile Iron, there is relatively little loss of strength as the nodularity decreases to 70% but as nodularity deteriorates further, strength decreases more rapidly.

The effect of nodularity on elongation can be inferred by considering the influence of nodularity on the difference between the yield and tensile strengths, which is proportional to elongation. Both Mg- and Pb-controlled losses in nodularity reduce the difference between the yield and tensile stresses, indicating that loss of nodularity results in reduced elongation. The dramatic decrease in tensile strength produced by lead control indicates that the formation of spiky, intercellular graphite can severely embrittle ductile Iron.

Designers can virtually eliminate the effect of nodularity on tensile properties by specifying that the nodularity should exceed 80-85% and that there should be no intercellular flake graphite. These criteria can be met easily by good production practices which ensure good nodularity through Mg control and prevent flake or spiky graphite by a combination of controlling flake-producing elements and eliminating their effects through the use of small additions of cerium [11].

2.1.13.2. Effect of Nodule Count

Nodule Count, expressed as the number of graphite nodules/mm^2, also influences the mechanical properties of Ductile Iron, although not as strongly and directly as graphite shape. Generally, high nodule count indicates good metallurgical quality, but there is an optimum range of nodule count for each section size of casting, and nodule counts in excess of this range may result in a degradation of properties. Nodule count per se does not strongly affect tensile properties, but it has the following effects on microstructure, which can significantly influence properties,

- ❖ Nodule count influences the pearlite content of as-cast Ductile Iron. Increasing the nodule count decreases the pearlite content, decreasing strength and increasing elongation.
- ❖ Nodule count affects carbide content. Increasing the nodule count improves tensile strength, ductility and machinability by reducing the volume fractions of chill carbides, segregation carbides, and carbides associated with "inverse chill".
- ❖ Matrix homogeneity is influenced by nodule count. Increasing the nodule count produces a finer and more homogeneous microstructure. This refinement of the matrix structure reduces the segregation of harmful elements which might produce intercellular carbides, pearlite or degenerate graphite.

❖ Nodule count affects graphite size and shape. Increasing nodule count results in a decrease in nodule size which improves tensile, fatigue and fracture properties. Inoculation practices used to improve nodule count often make the nodules more spherical. Thus, high nodule count is generally associated with improved nodularity [11].

2.1.13.3. Effect of Matrix

In Ductile Irons with consistent nodularity and nodule count and low porosity and carbide content, 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. Ferrite is the purest iron phase in Ductile Iron. It has low strength and hardness, but high ductility and toughness and good machinability. Pearlite is an intimate mixture of lamellar cementite in a matrix of ferrite. Compared to ferrite, pearlite provides a combination of higher strength and hardness 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 iscontrolled in the as-cast condition by controlling the composition of the iron, taking into account the cooling rate of the casting. It can also be controlled by an annealing heat treatment to produce a fully ferritic casting, or by normalizing to maximize the pearlite content [11].

2.1.13.4. Effect of silicon

Silicon enhances the performance of Ductile Iron at elevated temperatures by stabilizing the ferritic matrix and forming a silicon-rich surface layer which inhibits oxidation. Stabilization of the ferrite phase reduces high temperature growth in two ways. First, silicon raises the critical temperature at which ferrite transforms to austenite. The critical temperature is considered to be the upper limit of the useful temperature range for ferritic Ductile Irons. Above this temperature the expansion and contraction associated with the transformation of ferrite to austenite can cause distortion of the casting and cracking of the surface oxide layer, reducing oxidation resistance. Second, the strong ferrite formation tendency of silicon stabilizes the matrix against the

formation of carbides and pearlite, thus reducing the growth associated with the decomposition of these phases at high temperature.Theoxidation protection offered by silicon increases with increasing silicon content. Silicon levels above 4% are sufficient to prevent any significant weight gain after the formation of an initial oxide layer [13].

2.1.13.5. Effect of molybdenum

Molybdenum, whose beneficial effect on the creep and stress-rupture properties of steels is well known, also has a similar influence on Ductile Irons. The addition of 0.5 % molybdenum to ferritic Ductile Iron produces significant increases in creep and stress rupture strengths, resulting in high temperature properties that are comparable to those of ascast steel containing 0.2 % carbon and 0.6 % manganese [13].

2.1.13.6. Effect of Manganese

The decomposition of austenite to ferrite plus graphite or to pearlite in spheroidal graphite (SG) cast iron 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%. [11-13].

2.1.13.7. Effect of Copper

 The effect of various additions of copper and the cooling rate on the temperature of the onset of the stable and metastable eutectoid reactions describes the conditions for the growth of ferrite and of pearlite. These reactions can develop 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 ductileiron the copper is kept between 0.4-0.8percent and is a contaminant in the ferritic grade [11-13].

2.1.13.8. 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 [11-13]. Fig 2.9 shows Microstructures of ductile cast iron with the addition of nickel.
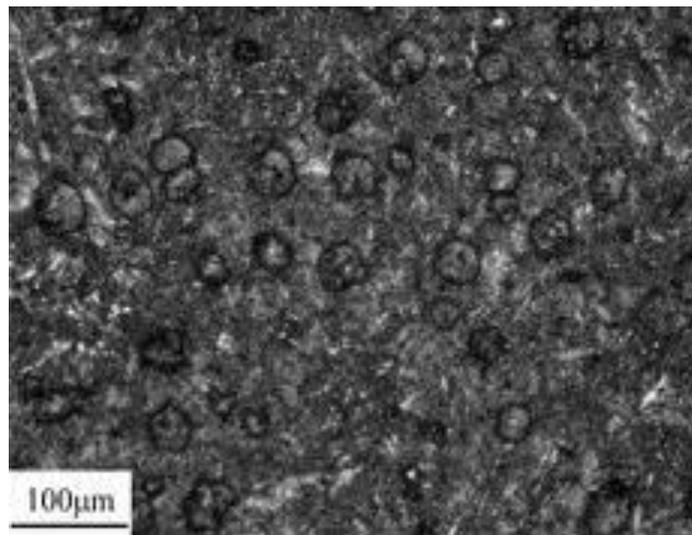
Fig. 2.9 Microstructures of ductile cast iron with the addition of nickel [14].

2.2. Quality Index of S.G. Iron

Quality Index for ductile iron was developed in a statistical study of mechanicalproperties of a large no of Ductile Iron samples by Siefer and Orths who identified a   relationship between tensile strength and Elongation in the form:

(Tensile Strength)^2 x (Elongation) = Q

Where, Q is a constant and was later referred to as a Quality Index for Ductile Iron. A larger value of Q indicates a combination of higher Tensile Strength and / or Elongation or both and is therefore indicative of a higher level of material performance.High Q value irons have been shown to result from high nodularity, high nodule count, structures with an absence of intercellular degenerate graphite, free from carbides, low phosphorus (< 0.03 %) and free from porosity. Fig 2.10 shows Quality index. Foundries seeking to optimize the fatigue strength of ductile iron castings need to produce high Q value material by taking actions to ensure:
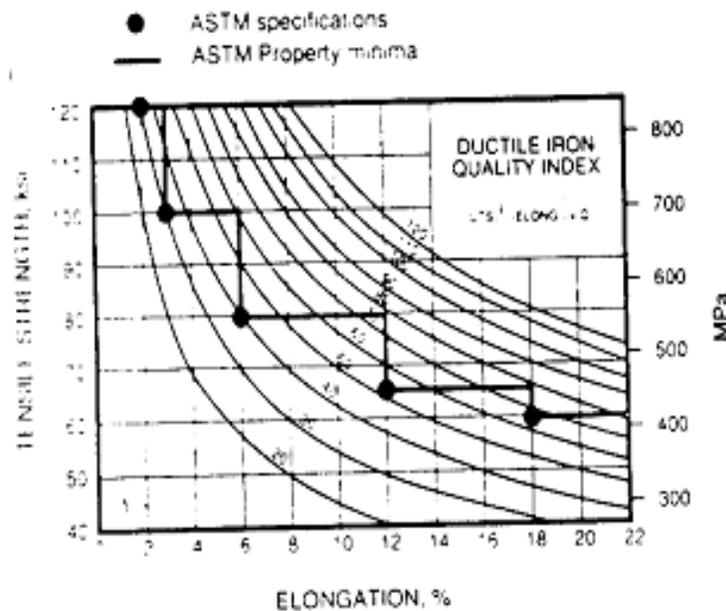
Fig. 2.10 Quality index [14].

- Achieving maximum pearlite and matrix hardness.
- Achieving high nodularity, high nodule count and small size of nodule.
- Achieving inclusion free casting.
- Eliminating shrinkage porosity.
- Low levels of tramp and residual elements.
- Minimum carbide content.

- Free from dross defect [14].

2.3. Ductile and Brittle Behavior of S.G. Iron:

All ferrous materials, with the exception of the austenitic grades shows a transition from ductile to brittle behavior when tested above and below a certain temperature known as transition temperature. A comprehensive treatment of the subject by Barton has been used to identify and discuss some of the factors affecting Ductile and Brittle behavior as follows.

Ductile failure is accompanied by considerable general or local plastic deformation, usually shown by visible distortion of a failed component and by slow crack extension or tearing. A ductile fracture appears black in a fully ferritic ductile iron and gray in pearlitic irons. Ductile fractures occur by tearing from the sites of graphite nodules along grain boundaries. So, the fracture contains numerous graphite nodules.

Brittle failure, by contrast, generally occurs without deformation, and very rapid crack propagation is involved. Brittle fractures in ductile irons are not associated with graphite sites and occur by cleavage of the metallic grains, usually before significant deformation has occurred. The separation through the grains very rapid and such fractures appears bright because the cleavage facets of the grains reflect light, a brittle fracture characteristically passes through the grains and very few, if any, graphite nodules are present along the fracture path. The transition temperature of a material is raised if loading speeds are high or if a notch is present. For this reason, brittle fractures are more commonly observed during impact testing then there during normal tensile testing. It is important to appreciate, however, that brittle failure can occur under normal tensile loading if the conditions favors this mode of failure. A simplified explanation for this ductile – to – brittle transition behavior is shown in figure 2.11, at higher temperatures, the stress required to cause plastic deformation is relatively low and failure occurs in a ductile manner, with considerable deformation, before the stress to trigger brittle failure by cleavage is exceeded. The stress required to cause plastic yielding increases rapidly as the temperature is decreased, and the stress required to produce brittle fracture may then be exceeded before plastic yielding can take place [15, 16].
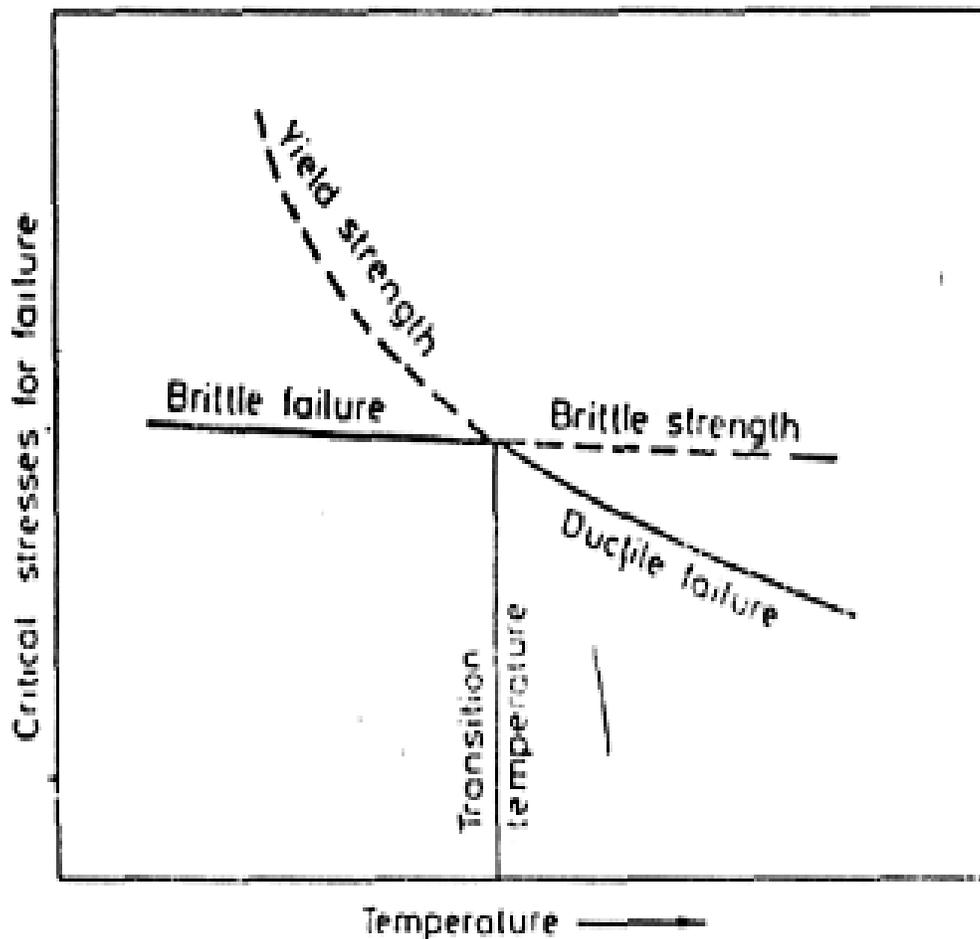
Fig.2.11 Ductile to Brittle transition occurs as temperature increases [16].

2.4. Austempered ductile iron

2.4.1. 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 [17]. Fig 2.12 shows Austempering process.

Process

1) Heat castings in a molten salt bath to austenitising temperature (815-927°C)
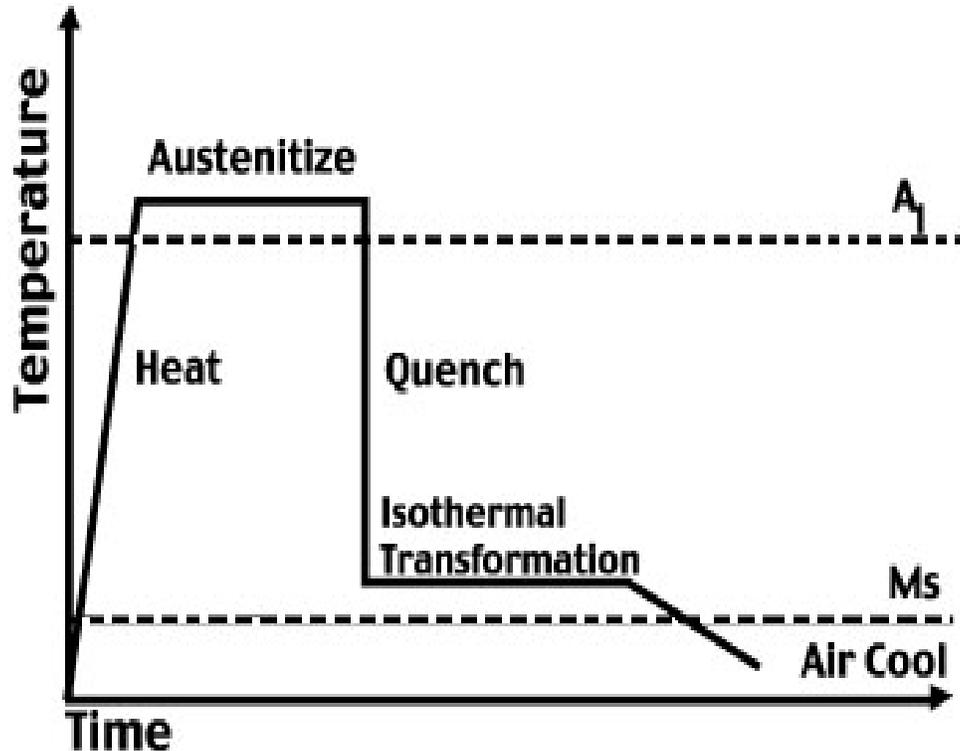
Fig.2.12 Austempering process [17].

2) Hold at austenitizing temperature to saturate the austenite with carbon.

3) Quench quickly to avoid pearlite to the austempering temperature in the range of 232-400°C (This temperature is above the martensite start temperature (Ms) for the material).

4) Hold at austempering temperature (232-400^{0}C) in molten salt bath for isothermal transformation to ausferrite [18].

Consistent control of times and temperatures throughout the entire process

1) Initial austenitising times and temperatures (1550° to 1700° F.) are controlled to ensure formation of fine grain austenite and uniform carbon content in the matrix. The precise temperature is grade dependant.
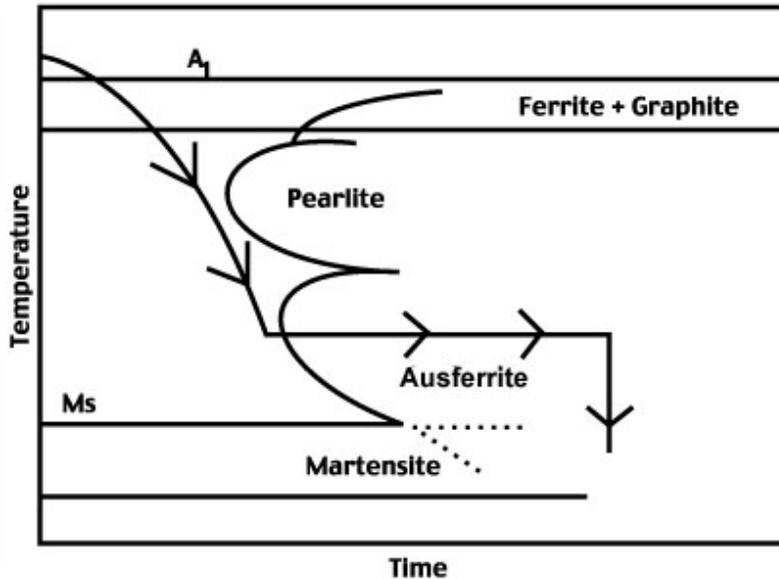
Fig.2.13 Control of time and temperature on the process [18].

2) Quench time must be controlled within a few seconds, to avoid formation of pearlite around the carbon nodules, which would reduce mechanical properties. Quench temperatures (450° to 750° F.) must stay above the point of martensite formation.

3) In the austempering step which follows austenitising, the temperature of the final salt bath must also be closely controlled. The austempering step is also precisely time-controlled, to avoid over- or under-processing. By the end of this step, the desired ADI ausferrite structure will be developed [18]. Fig 2.12 shows Control of time and temperature on the process.

2.4.1.1. Austenitising

The austenitising temperature controls the carbon content of the austenite which, in turn, affects the structure and properties of the austempered casting. High austenitising temperatures increase the carbon content of the austenite, increasing its hardenability, but at the same time make the transformation during austempering more problematic and worsen different 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.Austenitising time should be the minimum required to heat the entire part to the desired austenitising temperature and to saturate the austenite with the equilibrium level of carbon, (typically about 1.1-1.3%). In addition to the casting section size and type, the austenitising time is affected by the chemical composition, the austenitisingtemperature and the nodule count [19].

2.4.1.2. Austempering

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

- ❖ Transfer time from the austenitising environment to the austempering environment
- ❖ The quench severity of the austempering bath
- ❖ The maximum section size and type of casting being quenched
- ❖ The hardenability of the castings
- ❖ The mass of the load relative to the quench bath.

The use of a correctly designed austempering system with a suitably high quench severity, and the correct loading of castings, can minimize hardenability requirements of the casting resulting in significant savings in alloy costs [19].

To produce ADI with lower strength and hardness but higher elongation and fracture toughness, a higher austempering temperature 350-400°C should be selected to produce a coarse ausferrite matrix with higher amounts of carbon stabilized austenite(20-40%).

Once the austempering temperature has been selected,the austempering time must be chosen to optimize properties through the formation of a stable structure of ausferrite. At short

austempering times, there is insufficient diffusion of carbon to the austenite to stabilize it, and martensite may form during cooling to room temperature.The resultant microstructure would have a higher hardness but lower ductility and fracture toughness. Excessive austempering times can result in the decomposition of ausferrite into ferrite and carbide (bainite) which will exhibit lower strength, ductility and fracture toughness. At the highest austempering temperature 400°c as little as 30 minutes may be required to produce ausferrite. At 230°C as much as four hour may be required to produce the optimum properties.

At temperatures below that range the hardness may increase but the strength may decrease due to the presence of martensite mixed in with the ausferritematrix.

2.4.2. Austempered ductile iron

Austempered ductile iron is the most recent addition of the ductile iron family. It is produced by giving conventional ductile iron toaustempering heat treatment [19]. 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 [21].

Austempered Ductile Iron (ADI) offers the best combination of low cost, design flexibility, good machinability, high strength-to-weight ratio and good toughness, wear resistance and fatigue strength properties. Because it can be cast like any other member of the Ductile Iron family it offers all the production advantages of a conventional Ductile Iron casting. Subsequently it is subjected to the austempering process to produce mechanical properties that are superior to conventional ductile iron, cast and forged aluminum and many cast and forged steels [23].

The mechanical 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 [20].

2.4.2.1. Microstructure

Ductile Cast Iron undergoes a remarkable transformation when subjected to the austempering heat process. 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 first austenitised to dissolve carbon, then quenched rapidly to the austempering temperature to avoid the formation of deleterious pearlite or martensite.

While the casting is held at the austempering temperature nucleation and growth of acicular 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 enhances the bulk properties. Furthermore, while the austenite is thermodynamically stable, it can undergo a strain-induced transformation when locally stressed, producing 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 (as shown in figure 2.14) [24].
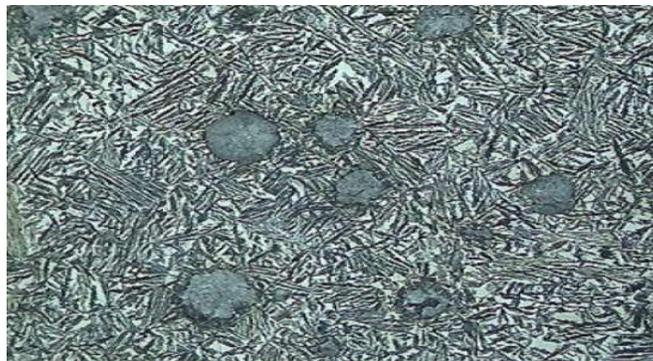

Fig. 2.14 Microstructure of austempered ductile iron [24]

2.4.2.2. Composition

In many cases, the composition of an ADI casting differs little from that of a conventional Ductile Iron casting. When selecting the composition, and hence the raw materials, for both conventional Ductile Iron and ADI, consideration should be given first to limiting elements which adversely affect casting quality through the production of non-spheroidal graphite, or the formation of carbides and inclusions, or the promotion of shrinkage. The second consideration is the control of carbon, silicon and the major alloying elements that control the hardenability of the iron and the properties of the transformed microstructure. When determining the alloying requirements both the section size and type and the severity (or speed) of the austempering quench must be considered [19].

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 austempered quench with water saturation section sizes of up to ¾ inch (20 mm) can be through hardened with no additional alloying. For castings of heavier section size selective alloying is required to through harden the parts and avoid pearlite in the heat treated microstructure [19].

2.4.2.3. Different grades of austempered ductile iron

Table2.2 Grades of austempered ductile iron [22].

Ref. Grade #	ASTM A897 Grade	Tensile Strength	Yield Strengths	Elongation	Brinell Hardness
1	130-90-09	130,000 p.s.i.	90,000 p.s.i.	9 %	269-341
2	150-110-07	150,000 p.s.i	110,000 p.s.i	7 %	302-375
3	175-125-04	175,000 p.s.i.	125,000 p.s.i.	4 %	341-444
4	200-155-02	200,000 p.s.i	155,000 p.s.i.	2 %	388-477
5	230-185-1	230,000 p.s.i.	185,000 p.s.i.	1 %	402-512

2.4.2.4. Effect of alloying elements

2.4.2.4.1. Carbon

Increasing carbon in the range 3 to 4% increases the tensile strength but has negligible effect on elongation and hardness. Carbon should be controlled within the range 3.6-3.8% except when deviations are required to provide a defect-free casting [19, 20].

2.4.2.4.2. Manganese

Manganese can be both a beneficial and a harmful element. It strongly increases hardenability, but during solidification it segregates to cell boundaries where it forms carbides and retards the austempering reaction. As a result, for castings with either low nodule counts or section sizes greater than 3.4 in. (19mm), manganese segregation at cell boundaries can be sufficiently high to produce shrinkage, carbides and unstable austenite. These microstructural defects and inhomogeneities decrease machinability and reduce mechanical properties. To improve properties and reduce the sensitivity of the ADI to section size and nodule count, it is advisable to restrict the manganese level in ADI to less than 0.3%. The use of high purity pig iron in the ADI charge offers the twin advantages of diluting the manganese in the steel scrap to desirable levels and controlling undesirable trace elements [19, 20].

2.4.2.4.3. Silicon

Silicon is one of the most important elements in ADI because it promotes graphite formation, decreases the solubility of carbon in austenite, increases the eutectoid temperature, and inhibits the formation of bainitic carbide. Increasing the silicon content increases the impact strength of ADI and lowers the ductile-brittle transition temperature. Silicon should be controlled closely within the range 2.4-2.8% [13, 17].

2.4.2.4.4. Nickel

Up to 2% nickel may be used to increase the hardenability of ADI. For austempering temperatures below 675^oF (350^oC) nickel reduces tensile strength slightly but increases ductility and fracture toughness [19, 20].

2.4.2.4.5. Molybdenum

Molybdenum is the most potent hardenability agent in ADI, and may be required in heavy section castings to prevent the formation of pearlite. However, both tensile strength and ductility decrease as the molybdenum content is increased beyond that required for hardenability. This deterioration in properties is probably caused by the segregation of molybdenum to cell boundaries and the formation of carbides. The level of molybdenum should be restricted to not more than 0.2% in heavy section castings [19, 20].

2.4.2.5. Advantages of Austempered Ductile Iron:

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

2.4.2.5.1. Tensile and Yield Strength:

ADI's tensile and yield strengths are at least twice those of standard ductile irons.

2.4.2.5.2. Fatigue Strength:

ADI's fatigue strength is typically 50% higher than that of standard ductile irons. It can be further increased by shot peening or fillet rolling. The lower hardness grades of ADI work well in structural applications.The fatigue strength of ADI compared to other materials are shown in figure 2.15.
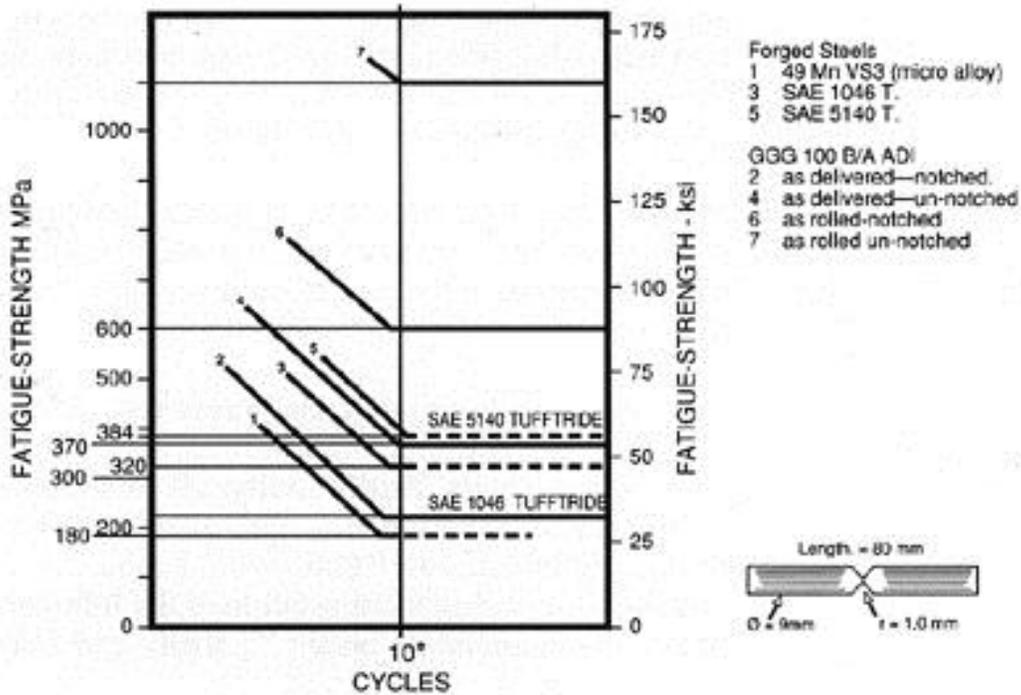
Fig. 2.15Fatigue strength compared to other materials [20].

2.4.2.5.3. Toughness:

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

2.4.2.5.4. Less weight

ADI weighs only 2.4 times more than aluminum and is 2.3 times stiffer. ADI is also 10% less dense than steel. Therefore, when you compare the relative weight per unit of yield strength of ADI with that of various aluminum alloys and steels, it is easy to see the engineering and design advantages inherent in ADI. The weights of ADI compared to other steels are shown in figure 2.16.
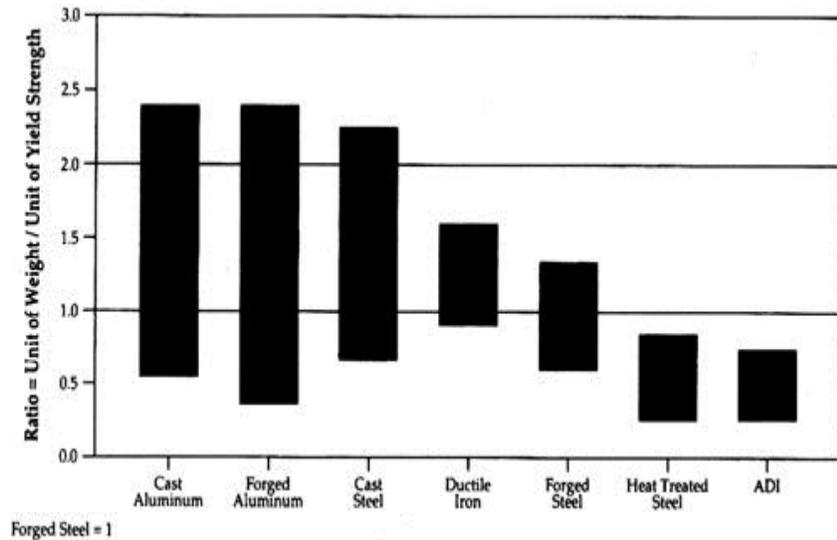
Fig. 2.16Less weight compared to the other steels [20].

2.4.2.5.5. Wear Characteristics:

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

2.4.2.5.6. Cost-effectiveness:

ADI is usually 15% to 20% less costly than steel forgings or castings. It is the most economical way of obtaining tensile, yield, or fatigue strength. ADI often competes favorably with heat-treated and alloy steels for heavy-duty applications where reliability is crucial. It is a useful upgrade from standard grades of ductile iron. In some cases it replaces manganese steel and nickel-chrome iron. Because of ADI's high strength-to-weight ratio, it has even replaced aluminum where the design allows reduced section sizes (shown in figure 2.17) [20].
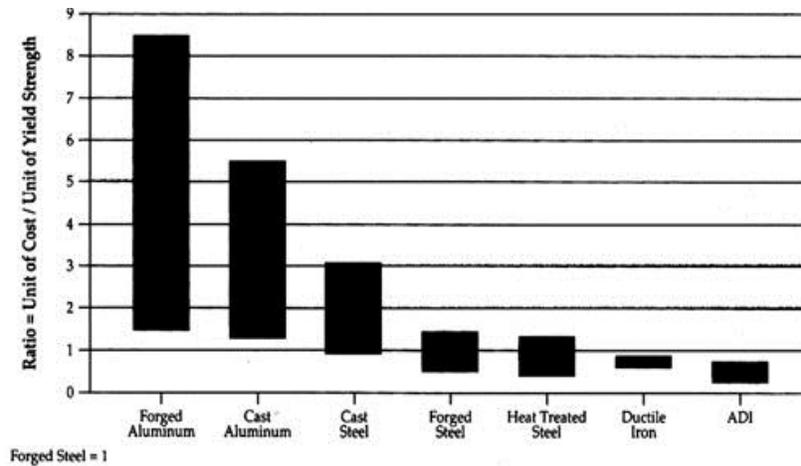
Fig. 2.17Relative cost per unit of yield strength [20]

2.4.2.6. Properties of ADI Compared to Steel:

❖ ADI is much easier to cast than steel

❖ ADI is approximately 9% lighter than steel

❖ ADI has minimal draft requirements compare with steel forgings

❖ ADI loses less of its toughness than steel at sub-zero temperatures

❖ ADI work hardens when stressed

❖ ADI has more damping capacity than steel[25]. Fig 2.18 shows Properties of ductile iron compared steels.
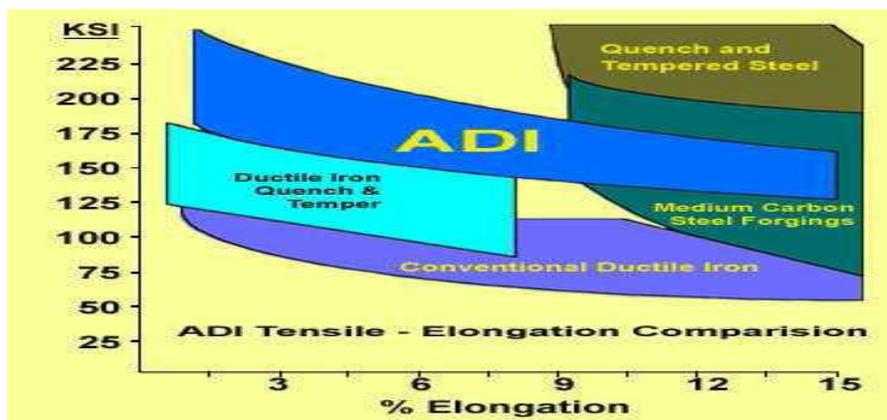
Fig. 2.18Properties of ductile iron compared steels [25].

2.4.2.7. Disadvantages of ductile iron

Materials specifiers should look beyond limited mechanical property data when replacing steel parts with ADI. For example, welding is not recommended for ADI parts. In some instances, the stiffness of the design must be increased to compensate for ductile iron's lower modulus of elasticity. Also, larger fillet radii are required than for steel to avoid stress concentrations. To take maximum advantage of ADI when substituting for forgings, some designs should be modified. Another desirable property of ADI is its work-hardening, which provides better rolling and sliding wear properties. However, because of this characteristic, consideration must be given to the sequence of operations when machining is required. The lower hardness grades can be machined after heat-treatment, but the higher hardness grades must be machined before heat treatment [27].

2.4.2.8. Applications of austempered ductile iron

The development and commercialization of Austempered Ductile Iron (ADI) has provided the design engineer with a new group of cast ferrous materials which offer the exceptional combination of mechanical properties equivalent to cast and forged steels and production costs similar to those of conventional Ductile Iron. In addition to this attractive performance: cost ratio, ADI also provides the designer with a wide range of properties, all produced by varying the heat treatment of the same castings, ranging from 10-15% elongation with 125 Ksi (870 MPa) tensile strength, to 250 ksi (1750 MPa) tensile strength with 1-3% elongation. Although initially hindered by lack of information on properties and successful applications, ADI has become an established alternative in many applications that were previously the exclusive domain of steel castings, forgings, weldments, powdered metals and aluminum forgings and castings [28].

The ADI market represents nearly all segments of manufacturing. Bellow fig shows the approximate break down of the ADI market. Fig 2.19 shows ADI market distribution.

Fig. 2.19 ADI market distribution [24].

Heavy Truck and Bus Components

Economic growth drives the need to haul heavier loads over longer distances, resulting in more time between vehicle maintenance and some difficult engineering challenges. The Heavy Truck industry recognized the potential benefits of Austempering solutions many years ago. Manufacturers took advantage of the versatility of ADI to introduce innovative light weight, high performance parts.Diesel Engine Timing Gears, Hypoid Ring and Pinion Gears,Jack Stand Gears, Wheel Hubs, Suspension Brackets these are some components which are manufactured by using austempering ductile iron [24-28].

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 housings, top caps and friction wedges, track plates, repair vehicle wheels, nipper hooks, and car wheels [24-28].

Construction Equipment

Heavy duty and hardworking, construction equipment can benefit greatly from the use of tough, wear resistant Austempered Irons and Steels. Whether for ground engaging components such as bucket teeth or engine and powertrain parts, ADI and other Austempered materials can improve the performance of your equipment [24-28].

Light Vehicle

The automotive industry is constantly looking to increase performance, and reduce the cost and weight of the vehicles they produce.Austempered materials have a proven track record of providing strength and dependability for safety components, suspension systems, and drivetrain applications [24-28].

Miscellaneous Industrial

Miscellaneous industrial applications include brackets, lever arms, knuckles, shafts, cams, sway bars, sleeves, clevises, conveyor components, jack components, bushings, rollers, molding line components, fixtures, gears, sprockets, deck plates, and all sorts of power transmission and structural components [24-28].

Agricultural

Farming and agricultural applications for ADI include plow points, till points, trash cutters, seed boots, ammonia knives, gears, sprockets, knotter gears, ripper points, tractor wheel hubs, rasp bars, disk parts, bell cranks, lifting arms, and a great variety of parts for planters, plows, sprayers and harvesters [28].

Sporting Goods

Even the sports goods industry has adopted ADI for its high strength to weight and superior wear resistance.Bobsleigh runners, Sword blades, Gun components are manufacturing by using austempered ductile iron [24].

Defense

The defense industry has been relatively slow to adopt ADI, however some of the applications include track links, armor, ordnance and various hardware for trucks and armored vehicles [28].

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. Diesel Engine Timing Gears, Hypoid Ring and Pinion Gears, Off-Highway Drive Axles, Ring Gears, Gear Housings, Sprockets, CV Joints, Differential Housings, Wheel Hubs etc. are prepared by using austempered ductile iron [24].

A brief discussion of previous works

CHAPTER 3   A brief discussion on previous work

Form the available literatures, it is quite evident 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 variablesand possible applications. A brief review of some literatures in theseareas is presented hereunder.

Olivera Eric, DraganRajnovic, Slavica, LeposavaSidjanin, T.Jovanovic have 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 effect of copper and copper plus nickel on the microstructure and impact properties of the two types ofaustempered ductile irons. They told that addition of copper plus nickel delays the transformation kinetics of the residual austenite resulting in a shift of the maximum of volume fraction 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 demonstrated 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 [29].

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 work they have taken one type of ductile iron sample and two types of steel samples and austempered 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 is increased so does the ferrite lath spacing and the volume fraction of retained austenite.The tensile strength and hardness decrease with austempering temperature while the elongation and impact toughness indicate significant increase as the austempering temperature is

raised. The good wear resistance exhibited 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 [30].

Z.K.Fan and R.E.Smallman have studied the fracture behavior of the austempered aluminum spheroidal graphite iron. For that they have taken the specimens of   Aluminum spheroidal graphite iron containing, 3.2%C, 2.2%A1, 0.3%Si by weight by weight 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 significantly 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 [31].

Uma Batra, S.Ray and S.R.Prabhakar studied on the variation in the austempered microstructure, the volume fraction of retained austenite, the average carbon content of retained austenite, their productand 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. From their work they observed that increasing austempering temperature changes the bainite Morphology from lower bainitic to upper bainite. The average 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[32].

F.Y. Hung, L.H. Chen, T.S. Lui studied the particle erosion of upper bainitic austempered ductile iron. In this work 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 Al2O3 particles of 275µm grit 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 demonstrated 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[33].

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 effect of alloying additions on the austempering kinetics using the Avrami equation. They observed 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[34].

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 austenitised the samples at 860^0C for one hour and then austempered at 320^OC and 400^0C in varying the time from 0.5 to 5 hours. They observed from their work is that the Austempering at 320^oC in the range between 2 and 5h 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 (40vol%) which was reached after 2.5h. The whole range of austempering time at 400^oC is distinguished by the presence of blocky austenite in which martensite was formed during subsequent cooling to the room temperature. During austempering at 400^oC yield strength, tensile strength and ductility are twice as lower than at 320^oC. The low values of tensile properties coincide with the appearance of martensite in the microstructure[35].

J. Aranzabal, I. Gutierrez, J.M. Rodriguez-I-babe, and J.J. UrcolaR have studied on the influence of the amount and morphology of austenite phase on the mechanical properties (proof stress, ultimate tensile strength (UTS), elongation and toughness) at different austempering conditions. They concluded from their work that the short time treatmentslead to deteriorated mechanical properties in accordance with the presence of un-tempered martensite. The combination of long times 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 thefiner distribution of this phase in the microstructure. The bainitic ferrite and the austenite contribute in this case to the proof stress of the material, and the increase of the austenite volume fraction has beneficial 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^oC 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 %, 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 exhibits 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: ''austempered'' 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 [36].

A.S.M.A. Haseeb, Md. Aminul Islam, Md. Mohar Ali Bepari studied the behavior of ductile iron heat treated by two different procedures, quenching &tempering and austempering to identical matrix hardness. For that 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[37].

Srinivasamurthydaber, K.S.Ravishankar, P.PrasadRao 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.% molybdenum and 0.5 wt.% copper was subjected to austempering treatments which consisted of three austenitising temperatures, namely 850, 900 and 950° C, and three austempering temperatures, namely 300, 350 and 400^0 C. They were carried out tensile tests under all the heat-treatment conditions and strain-hardening behavior 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 [38].

M.NiliAhmadabadi, H. M.Ghasemi and M.Osia havestudied the effect of austemperingprocess on the wear behavior of austempered ductile iron ADI. For that 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 periods. 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 resultsthey told that successive austempering process improves both mechanicalproperties and wear resistance of ADI in comparisonwith conventional austempering process.The specimens with lower nodule count longer solidification time have lower wear rate than specimens withhigher nodule count shorter solidification time. High carbon content retained austenite along with goodmechanical properties is supposedly the main reason for improvement of wear resistance of HLAT specimens [39].

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 decreasedue 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 t_{AS}, andthese values increase as the austempering process progresses.The proof stress may decrease at longer t_{AS}, while the UTSremains, more or less, constant. Austempering the Cu-alloyedductile iron for 60 min at 270, 330, or 380 °C resulted in anADI 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 t_{AS} less than 30 min; however, these properties improve for t_{AS} of 60-150 min [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 studied 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: theupper bainite has a feathery-like morphology and thelower bainite has a plate-like one. These facts are,probably, a result of different crystallographic shears during the formation of the upper and lower bainite. A comparison of the dilatometrical data with the X-ray results shows that the bainite transformation ceases 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 a-phase volume fraction results in an increase of the volume fraction of high carbon austenite [41].

U. Batrawas 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 needleincreased. The morphology of the bainitic ferrite changes from lower to upper.The hardness, 0.2% proof stress, 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, thedeformation is limited to near thenodule only. However, it spreads intothe matrix for ADIs austempered at thehigher austempering temperatures of 330 and 380°C. The crack generallyinitiates from the graphite nodulesurface and propagates through thematrix of bainitic ferrite and retainedaustenite. It normally propagatesthrough bainitic ferrite/austeniteinterfaces when ferrite makes an anglegreater than 45°C with the applied loadbut it cuts through bainitic ferrite whenthe cluster of bainitic ferrite makes anangle less than 45°C

with the appliedload. Intercellular segregation andnonmetallic inclusions are the other probable locations for crack growth [42].

C.HakanGür, VolkanKilicli, Mehmet Erdogan have studied the mechanical properties of austempered ductile ironachieved through the heat treatment is conducted in a restricted time and temperature frame called the "processing window".In this study they have investigated MBN response and variations in microstructure and mechanical properties of austempered ductile iron. MBN measurements are sensitive to the fine evolutions of the austempering stages of austempered ductile iron. Martensite volume fraction gradually decreases and finally disappears with increasing the austempering time while the transformed austenite content decreases and acicular ferrite contents increases. By measuring the MBN parameters such as, the height and the position of MBN peak, the changes in the microstructure and corresponding variations in yield and tensile strengths, and total elongation can be estimated non-destructively [43].

C.Valdes, M.J. Perez Lopez, M. Figueroa, and L.E. Ramirezhave 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 austenitising temperature in the range of 780 to 830$^{\text{o}}$C for 90 minutes and then austempered at 375^{0}C for 60 minutes. From their work, they observed that as-cast microstructure was constituted by a ferrite-pearlite mixture of the bull-eye type with an average of graphite nodularity of 93% UTS, elongation and impact strength strongly depend onamounts of pro-eutectoid ferrite and ausferrite presentafter heat treatment.Unalloyed and 1Ni-0.24Mo ductile iron treated in the inter-critical region between 800–830$^{\text{o}}$C, exhibited the highestimpact strength from 140 to 145 J and from 100 to 130 J,respectively, due to presence of duplex matrix structure [44].

C.Z. Wu, Y.J. Chen andT.S. Shih have studied the phase transformation of austempered ductile iron by micro jet impact. For that they have austempered the ductile iron specimens at 320^{0}C and 360^{0}C with ultrasonic vibration treatment. They found from their work is that the content and morphology of retained austenite have a fundamental influence on the mechanical properties of ADI. Good ductility is exhibit within the matrix microstructure where a large volumefraction of

austenite has been retained and uniformly distributed overthe matrix, as in the case developed from Ni- andCu-alloyed ADI.After subjecting to ultrasonic treatment, someisland-like austenite is found to undergo a phasetransformation of austenite to martensite induced byshear stresses from impact of micro-jets and shockwaves, while some stringer-type austenite is found toprecipitate carbides.After the process, micro-hardness values areenhanced along with an increased cumulative treatment time. The values obtained in intercellularregions are much higher due to Mn segregation.The stress-induced transformed martensiteanalyzed by EPMA is found to have a higher content of Mn for island-like austenite, which appearswithout microcracks, and that having a lower content of Mn usually shows microcracks after ultrasonic treatment.The elastic strain-energy density estimated froma microjet impact on the surface of ADI varied from 5.1×10^3 to 9.2×10^4 J/m^3. In the homogeneous nucleation of a martensite nucleus, the elastic strain energy density is about 8.6×10^7J/m3. Apparently,this estimated elastic strain-energy density is fewer than the energy necessary for homogeneousnucleation of martensite [45, 46].

Yoon-Jun Kim, Hocheol Shin, Hyounsoo Park and Jong DaeLimhve studied how the mechanical properties of the austempered ductile cast iron varying with the austempering temperature. For that they have austenitized the samples alloyed with copper and molybdenum at 910°C for one hour and austempered at 350 and 410^{0}C temperatures. From their work they concluded thatCu and Mo alloyed iron blocks were cast and heat treated. Inorder to see the effect of austempering temperature onmechanical properties, blocks were austenitized at 910 °C for90 min, then quenched and held at 350, 370, 390 and 410 °Cfor 90 min. It was found that the higher austemperingtemperature, the higher ductility. The highest ductility wasobtained from410 °C austempered samples. However,tensilestrength was highest for 350 °C austempered cast iron.Based upon mechanical property investigations, ADIsproduced 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 as350 °C and 370 °C can be grouped as ASTM grade 2.Copper and molybdenum addition plays effective role in theformation of ausferrite structure as well as increment ofmechanical properties such as tensile strength and hardenability [47].

DongCherngWEN and TienShouLEI 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% copper and 0.5% nickel and austenitized at 900°C and austempered at 400°C.they found from their work is that themartensite content of ADI had a significantinfluence on Its mechanicalproperties. As martensitecontent Increased, ductility and toughness decreasedobviously. Theeffect of martensite on reducing mechanical properties could be eliminated after tempering at 200^{0} C.Ductility and toughness could be increasedwithout decreasing the previous strength, and the strengthening effects were particularly evident at 3-50 % martensite content. Tempering at 200^{0}C could shorten the austempering time in getting the samelevelas the peak valuesof mechanical properties of ADI treated with singleaustempering, and could extend the effective range ofaustempering time.Fromthe observation of mechanical propertiesand microstructure changes, itwasevident that the useof processing window defined by resistivity curve inselecting the isothermal holding time in austempering was effective and direct. When ductile iron wasaustempered within this processing window the mechanicalproperties satisfied the standard requirementwere obtained.

Materials and Methods

4.1 Materials

Three grades of ductile iron samples have used in the experiment which were produced in a commercial foundry known as L&T Kansbhal. The difference between these three grades is: first one is unalloyed, second one is Copper alloyed and third one is Nickel alloyed. Chemical composition of the three grades of ductile iron samples are given below in the table 4.1.

Table 4.1Chemistry of the S.G. iron

Sample	C	Si	Mn	Cr	Ni	Mg	Cu	S	P
Unalloyed	3.57	2.22	0.23	0.03	0.12	0.045	0.001	0.011	0.026
With copper	3.55	2.1	0.18	0.03	0.22	0.038	0.49	0.009	0.024
With Nickel	3.56	2.14	0.18	0.02	0.45	0.042	0.002	0.008	0.023

4.2 Test Specimen Preparation

For tensile test the solid block of ductile iron was cut to "Dog Bone Shape", which were machined to 6 mm gauge diameter and 30 mm gauge length. Fig 4.1 shows Test Specimen for tensile strength .
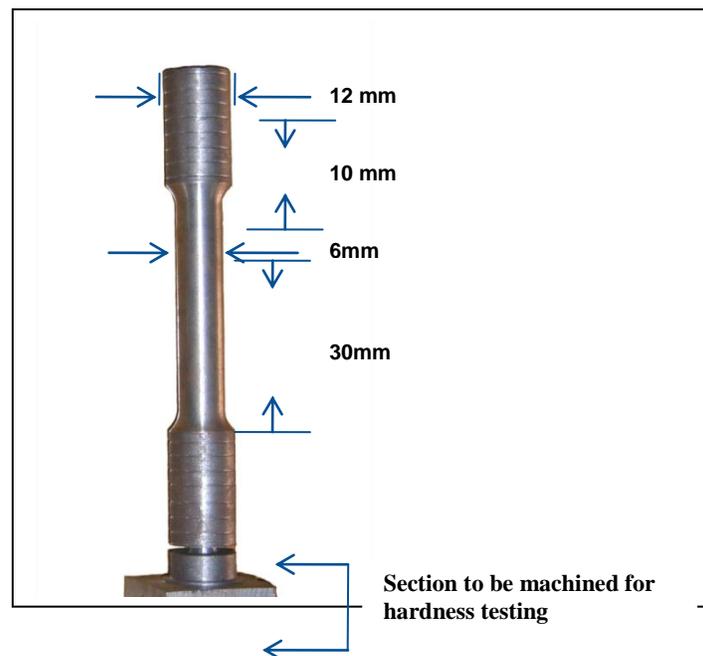
Fig. 4.1 Test Specimen

4.3 Heat Treatment (Austempering)

Number of samples of each grade have taken and heated to 900°C for one hour (austenisation) and then transferred quickly to a salt bath (salt combination was 50 wt % $NaNO_3$ and 50 wt % KNO_3) maintained at different temperatures(250°C,300°C,350°C) for 30 min, 60 min, 90 min and 120 min. Fig 4.2 shows Dog bone shaped ductile iron before and after austempering

| Before Austempering | After Austempering |

Fig. 4.2 Dog bone shaped ductile iron before and after austempering

4.4Hardness Measurement

The heat treated samples of dimension 8×8×3 mm were polished in emery papers(or SiC 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).

4.5 Tensile Testing

Tensile test were carried out according to ASTM (A 370-2002). A specimen of "Dog Bone Shape" shown in figure 4.1 was prepared for tensile test, which were machined to 6mm gauge diameter and 30 mm gauge length. Test was conducted by using universal testing machine (UTES 100) as per ASTM standard. Fig. 4.3 shows Specimen used for tensile properties
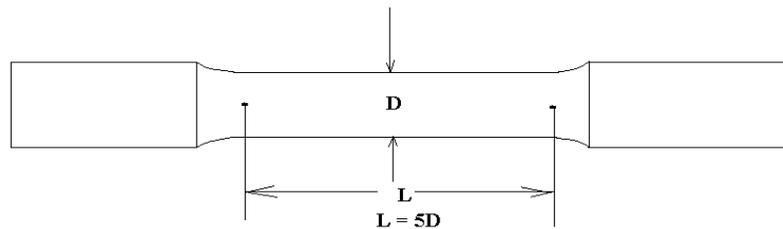
Fig. 4.3 Specimen used for tensile properties

Advanced materials are used in a wide variety of environments and at differenttemperature 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. In this investigation we have measured tensile strength, elongation, yield strength and hardness. Fig. 4.4 shows Fuel Instruments & Engineers Pvt Ltd UTM (Model: UTES-100)

Fig. 4.4Fuel Instruments & Engineers Pvt Ltd UTM (Model: UTES-100)

4.6 Scanning Electron Microscopy

4.6.1. Micro-structural observations

The samples were prepared for micro structural analysis. Fromeach specimen a slice of 4 mm is cut to determine the microstructure. These slices are firstlymounted by using Bakelite powder

then polished in SiC 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 differentheat treated specimen by using JEOL JSM-6480LV Scanning Electron Microscopy (SEM). Fig. 4.5 shows JEOL JSM-6480LV scanning electron microscope.

Fig. 4.5 JEOL JSM-6480LV scanning electron microscope

4.6.2.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 conditions are analyzed by using Scanning Electron microscopy (SEM).For this samples were cleaned withAcetone to remove any dust or impurity on the surface of specimens before SEM.

4.7 X-Ray Diffraction studies

The X-Raydiffraction (XRD) analysis was performed for few selected samples.Thistechnique was used to estimate the volume fractions of retained austenite and ferrite inthe material after treatment. XRD was performed 30 KV and 20 mA using a Cu- Kα targetdiffractometer. Scanning was done in angular range 2θ from 30° to 80° at ascanning speed of 2°/min. The profile was analyzed on computer by using X' Pert High ScoreSoftware to obtain the peak position and integrated intensities of the austenite and ferrite. Fig. 4.6 shows Philips X-pert MPD X-ray diffractometer.

Fig. 4.6 Philips X-pert MPD X-ray diffractometer.

Chapter 5

Results and discussion

CHAPTER 5	Results and discussion

In the present research work effect of different variables like austempering time, austempering temperature and alloying of Copper and Nickel on properties and microstructure of ductile iron have been studied.

5.1. The mechanical properties

The mechanical properties (tensile strength, yield strength, elongation & hardness) of the unalloyed,Copper alloyedand Nickel alloyed samples for various austempering time and temperature are summarized in Table 5.1, 5.2 and 5.3, respectively. Stress-Strain curves of unalloyed ADI austempered at 250 °C for 30 min, Cu-alloyed ADI austempered at 300 °C for 60 min and Ni-alloyed ADI austempered at 350 °C for 90 min are given in fig 5.1, 5.2 and 5.3, respectively.
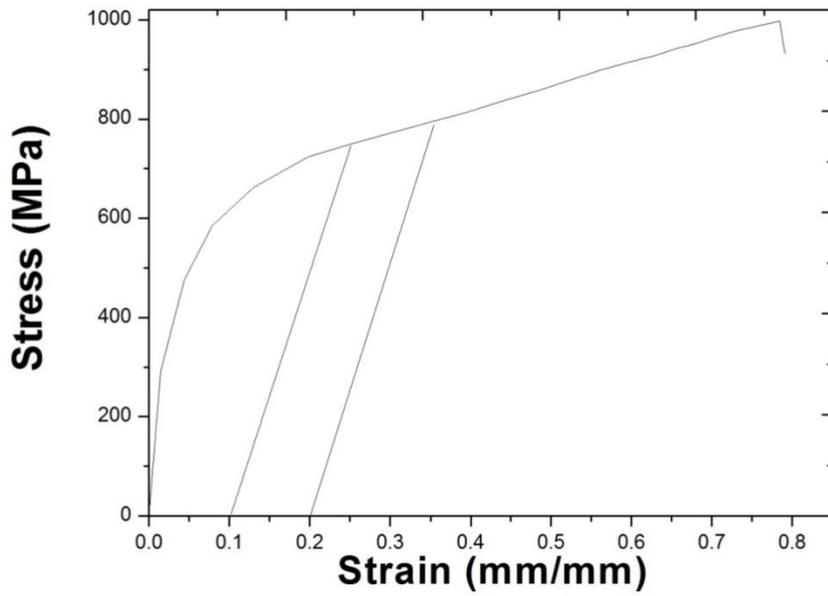
Figure 5.1 Stress-strain curve of unalloyed ADI austempered at 250 °C for 30 min.
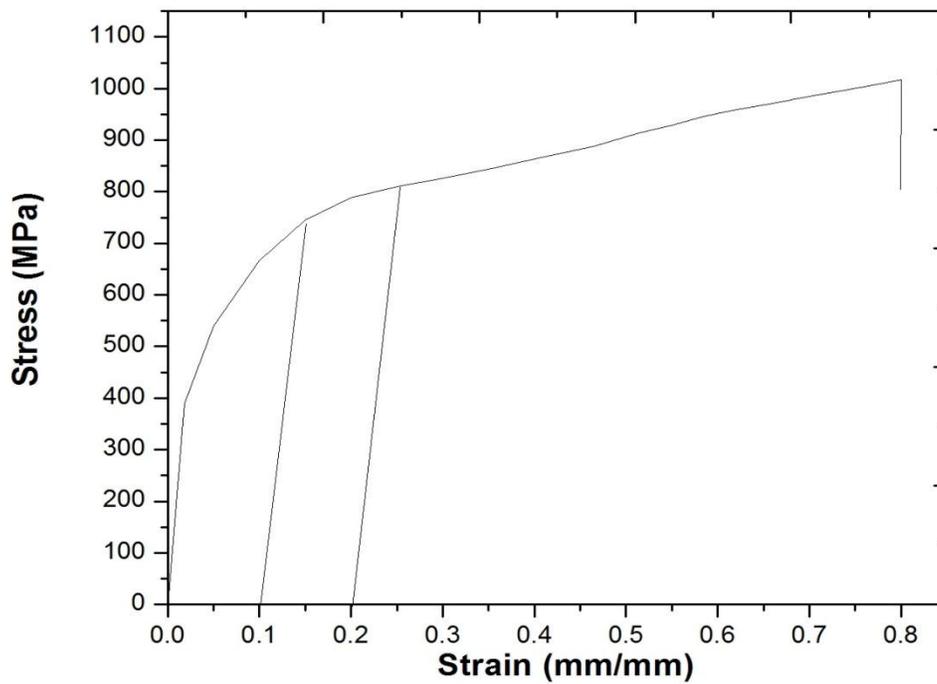
Figure 5.2 Stress-strain curve of Cu-alloyed ADI austempered at 300 °C for 60 min.
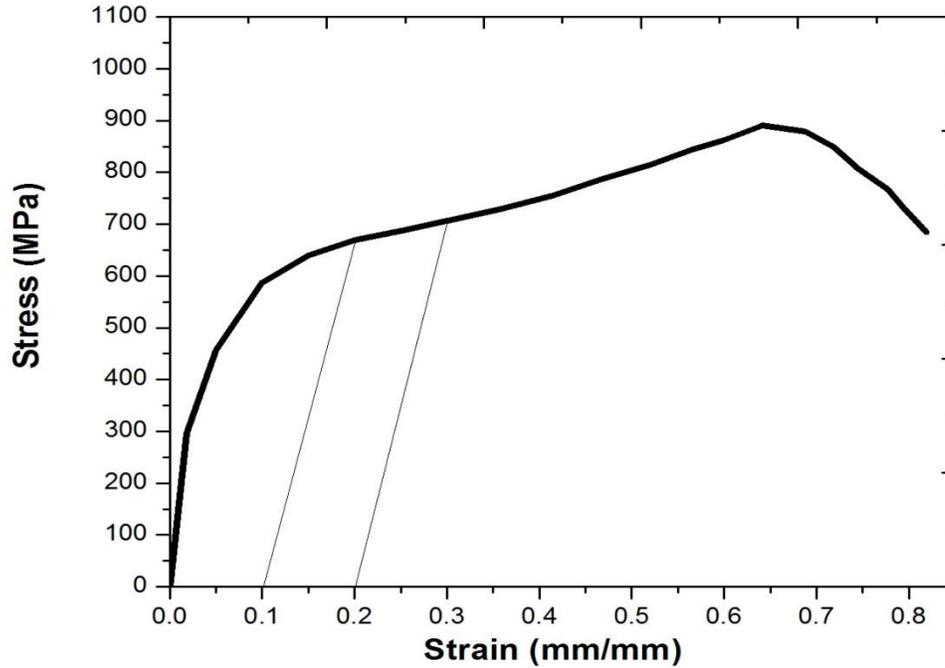
Figure 5.3 Stress-strain curve of Ni-alloyed ADI austempered at 350 °C for 90 min.

Table 5.1 Tensile strength, yield strength and elongation of Unalloyed ADI (without alloying Ni or Cu).

Austempering Temperature (°C)	Time (min)	Unalloyed ADI			
		Tensile strength, σ^{UTS}(MPa)	0.2% Yield strength, σ^{YS} (MPa)	Elongation (%)	Hardness (R_A)
250	30	997	795	1.9	75
	60	1139	957	2.4	80
	90	1124	927	2.8	79
	120	1116	906	2.8	78
300	30	831	693	3.7	69
	60	983	806	4.2	73
	90	965	759	4.8	71
	120	976	788	4.7	72
350	30	724	539	5.9	65
	60	871	691	6.7	69
	90	849	673	7.2	68
	120	861	687	7.1	67

Table 5.2 Tensile strength, yield strength and elongation of Copper alloyed ADI.

| Austempering Temperature (°C) | Time (min) | Copper alloyed ADI | | | |
		Tensile strength, σ^{UTS}(MPa)	0.2% Yield strength, σ^{YS} (MPa)	Elongation (%)	Hardness (R$_A$)
250	30	1039	834	1.5	76
	60	1181	995	2.1	82
	90	1162	967	2.4	80
	120	1168	978	2.3	79
300	30	873	685	3.1	71
	60	1017	825	3.5	74
	90	1034	858	3.7	72
	120	1030	851	3.8	73
350	30	778	591	5.2	68
	60	928	735	5.8	72
	90	921	733	5.9	70
	120	907	716	6	69

Table 5.3 Tensile strength, yield strength and elongation of Nickel alloyed ADI.

| Austempering Temperature (°C) | Time (min) | Nickel alloyed ADI | | | |
		Tensile strength, σ^{UTS}(MPa)	0.2% Yield strength, σ^{YS} (MPa)	Elongation (%)	Hardness (R$_A$)
250	30	1010	815	1.7	75.5
	60	1156	985	2.2	81
	90	1160	945	2.6	79.5
	120	1121	942	2.6	79
300	30	852	667	3.5	69.5
	60	1003	822	3.9	73.5
	90	1018	828	4.3	71.5
	120	997	805	4.4	72.5
350	30	757	565	5.5	67
	60	905	711	6.5	71
	90	889	698	6.9	69
	120	898	702	6.6	68

5.1.1. Effect of austempering time on UTS
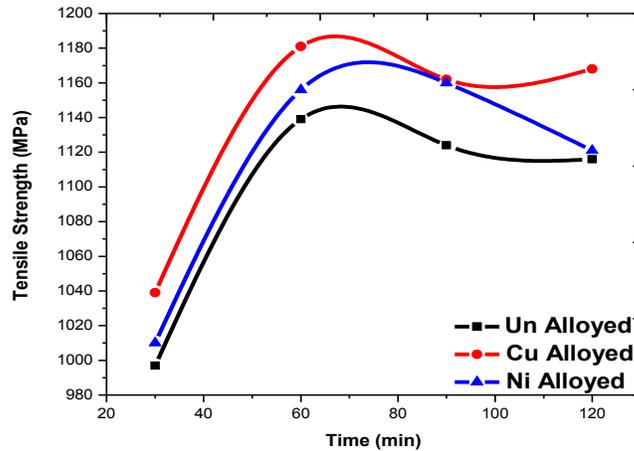
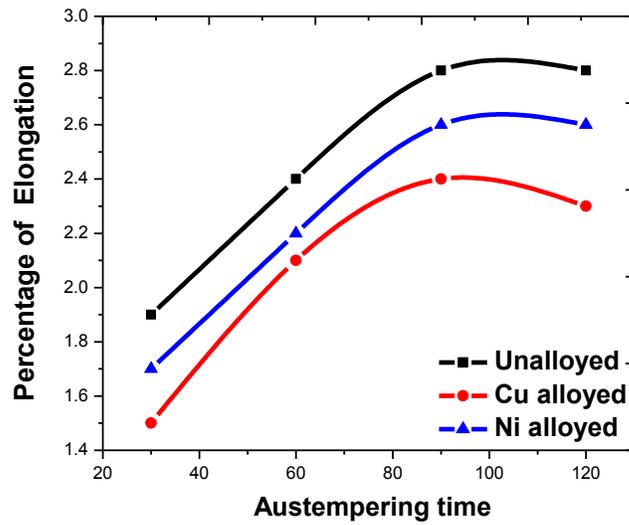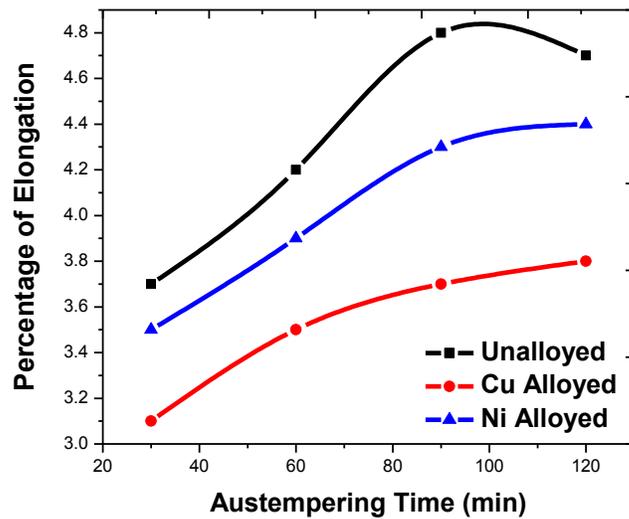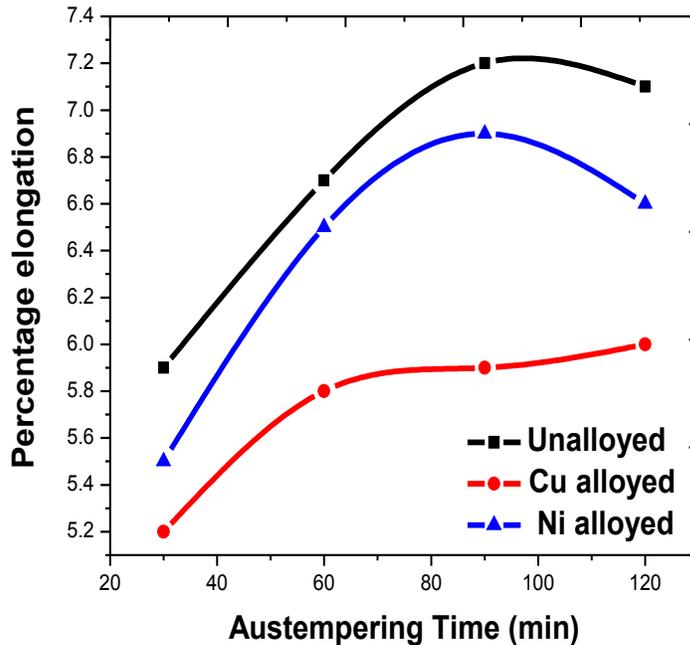Fig. 5.4 Effect of austempering time on UTS, austempered at 250 ˚C

Fig 5.4 is showing the variation of tensile strength with respect to the austempering time at temperature 250°C. Tensile strength is increasing from 30 min time to 60 min in the all samples but from 60 min to 90 min it is decreasing in un alloyed, Cu alloyed and increasing in Ni alloyed sample and from 90 min to 120 min increased in unalloyed iron, Cu alloyed whereas in Ni alloyed iron it is decreased.
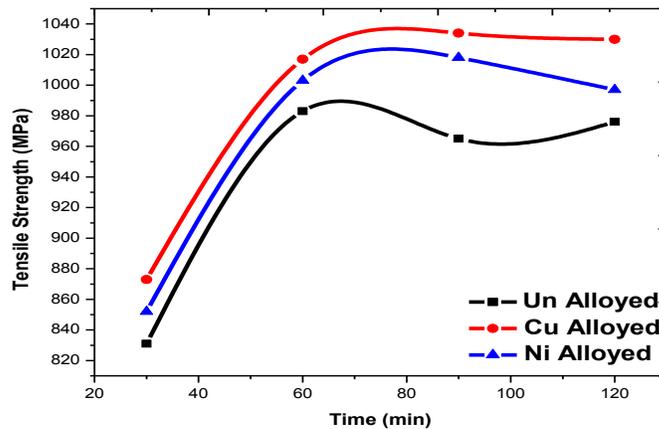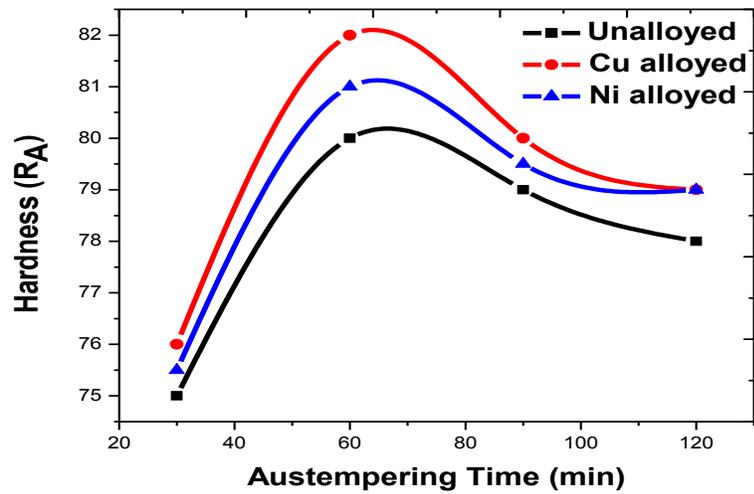

Fig. 5.5 Effect of austempering time on UTS, austempered at 300 ˚C

Fig 5.5 is showing the variation of tensile strength with respect to the austempering time at temperature 300°C. Tensile strength is increasing from 30 min time to 60 min in the all samples but from 60 min to 90 min it is decreasing in un alloyed and increasing in alloyed samples (Cu,

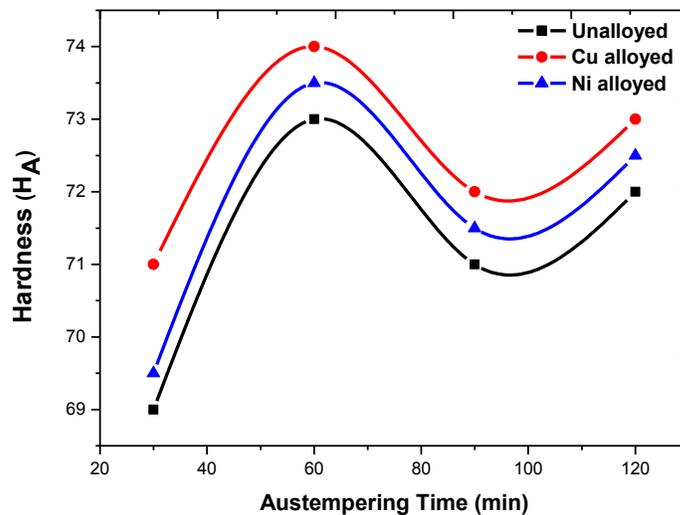Ni) and from 90 min to 120 min increased in unalloyed iron, Cu alloyed whereas in Ni alloyed iron it is decreased.
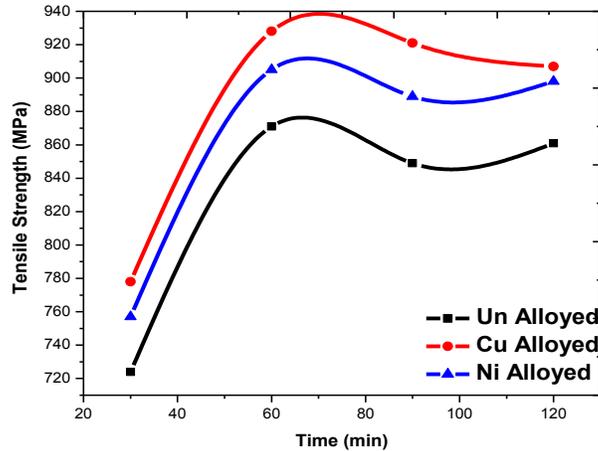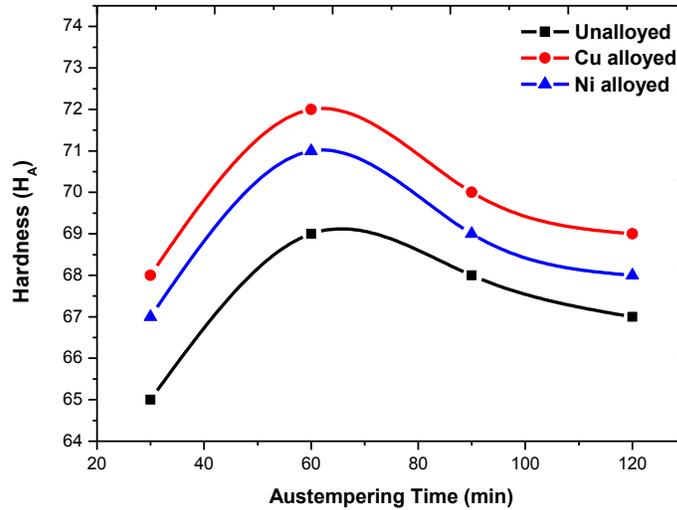

Fig. 5.6Effect of austempering time on UTS, austempered at 350 ˚C

Fig 5.6 is showing the variation of tensile strength with respect to the austempering time at temperature 300°C. Tensile strength is increasing from 30 min time to 60 min but from 60 min to 90 min it is decreasing in the all samples. from 90 min to 120 min TS increased unalloyed and Ni alloyed but decreased in Cu alloyed.

Three types of samples are almost showing same type of behavior with respect to the austempering time. Tensile strength is increasing from 30 min austempering time to 60 min, from 60 min to 90 min it is decreasing and from 90 min to 120 min sometimes increasing and sometimes decreasing. Overall it is observed that tensile strength is increasing from 30 min to 60 min and after that for 60 min, 90 min and 120 min tensile strength almost same i.e. not showing significance difference for both the grades. Austempered ductile iron alloyed with cooper is showing little bit higher strengths than the unalloyed austempered ductile iron.

5.1.2. Effect of austempering time on elongation

Fig. 5.7Effect of austempering time on elongation, austempered at250 ˚C

Fig5.7 is showing the variation of elongation with respect to the austempering time at temperature 250^oC. Elongation is increasing from 30 min austempering time to 90 minutes, and from 90 min to 120 min decreased in all the grades.

Fig. 5.8Effect of austempering time on elongation, austempered at 300 ˚C

Fig5.8 is showing the variation of elongation with respect to the austempering time at temperature 300°C. Elongation is increasing from 30 min austempering time to 90 minutes, and from 90 min to 120 min increased in Cu, Ni alloyed and decreased in unalloyed ductile iron.

Fig. 5.9Effect of austempering time on elongation, austempered at 350 ˚C

Fig5.9 is showing the variation of elongation with respect to the austempering time at temperature 350°C. Elongation is increasing from 30 min austempering time to 90 minutes, and from 90 min to 120 min increased in Cualloyed and decreased in Ni alloyed and unalloyed ductile iron.

Overall it is observed that Elongation is increasing from 30 min to 90 minand from 90 min to 120 min sometimes increasing and sometimes increasing in all the grades. Austempered ductile iron alloyed with cooper is showing little bit lower elongation thanthe unalloyed austempered ductile iron while ductile iron alloyed with nickel is showing intermediate value.

5.1.3. Effect of austempering time on hardness

Fig. 5.10 Effect of austempering time on hardness, austempered at 250 ˚C

Figure 5.10 is showing the variation of hardness with respect to the austempering time at temperature 250^oC. Hardness is increasing from 30 min time to 60 min but from 60 min to 90 min and from 90 min to 120 min decreased in the all samples.

Fig. 5.11 Effect of austempering time on hardness, austempered at 300 ˚C

Figure 5.11 is showing the variation of hardness with respect to the austempering time at temperature 250°C. Hardness is increasing from 30 min time to 60 min but from 60 min to 90 min and from 90 min to 120 min decreased in the all samples.

Fig. 5.12 Effect of austempering time on hardness, austempered at 350 ˚C

Fig 5.12is showing the variation of hardness with respect to the austempering time at temperature 350°C for all the grades. Hardness is increasing from 30 min austempering time to 60 min time, from 60 min to 90 min it is decreasing and from 90 min to 120 min sometimes increasing and sometimes increasing.

Overall it is observed that hardness is increasing from half an hour to one hour and for one hour, one and half an hour and two hours tensile strength almost same i.e. not showing significance difference for both the grades. Austempered ductile iron alloyed with cooper is showing little bit higher hardness thanthe unalloyed austempered ductile iron.
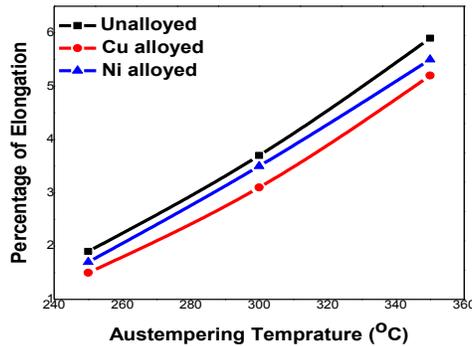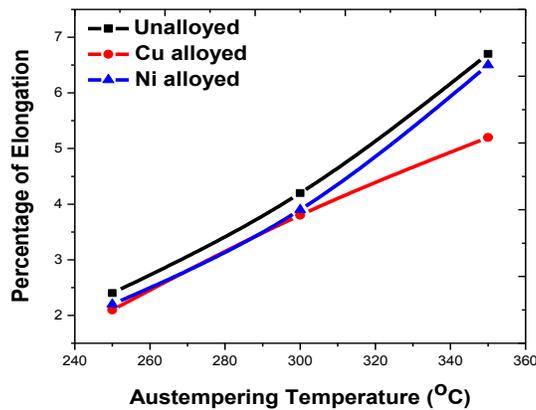
5.1.4. Effect of austempering temperature on UTS
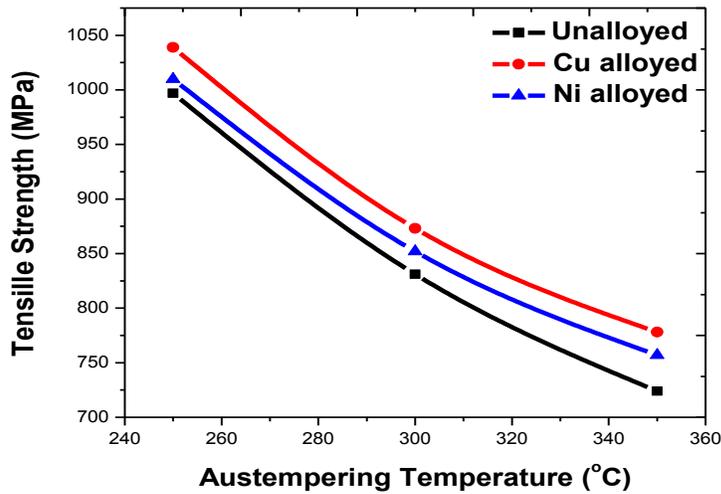
Fig. 5.13 Effect of austempering temperature on UTS for 30 min

Fig 5.13 is showing the variation of tensile strength with respect to the austempering temperature for 30 min. Tensile strength is decreasing with increasing austempering temperature in all the grades and Cu alloyed ductile iron showing high tensile strength and unalloyed one showing lower strength.
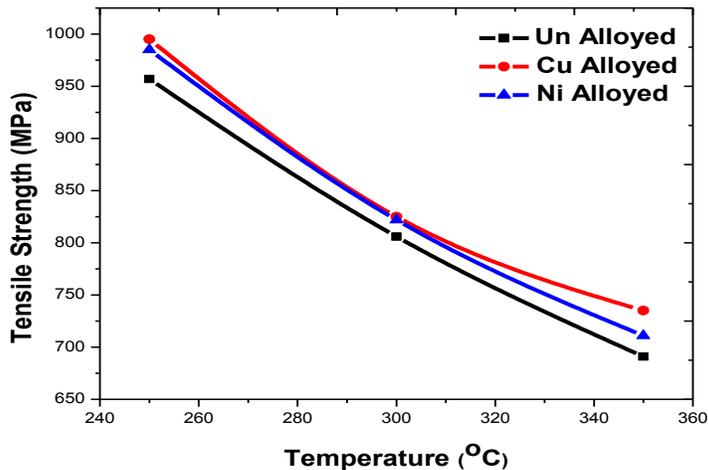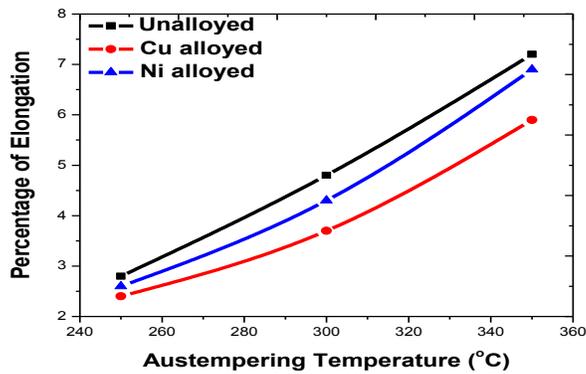

Fig. 5.14Effect of austempering temperature on UTS for 60 min

Fig 5.14 is showing the variation of tensile strength with respect to the austempering temperature for 60 min. Tensile strength is decreasing with increasing austempering temperature in all the

grades and Cu, Ni alloyed ductile iron grades showing almost same tensile strength and un alloyed one showing lower strength.
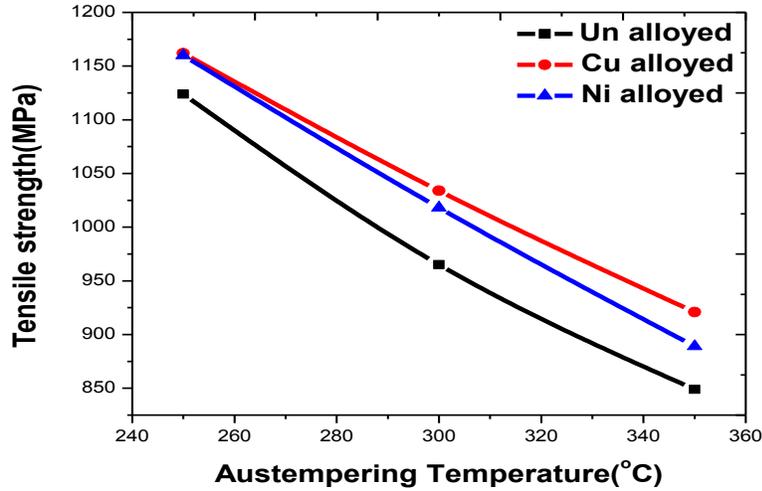
Fig. 5.15 Effect of austempering temperature on UTS for 90 min

Fig 5.15 is showing the variation of tensile strength with respect to the austempering temperature for 60 min. Tensile strength is decreasing with increasing austempering temperature in all the grades andCu alloyed ductile iron showing high tensile strength and un alloyed one showing lower strength.
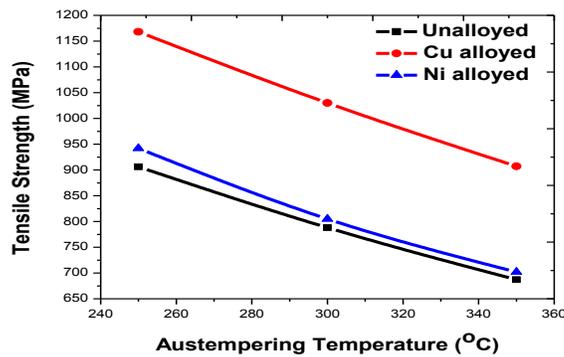
Fig. 5.16 Effect of austempering temperature on UTS for 120 min

Fig 5.16 is showing the variation of tensile strength with respect to the austempering temperature for 60 min. Tensile strength is decreasing with increasing austempering temperature in all the

grades and Cu alloyed ductile iron showing high tensile strength and un alloyed and Ni alloyed ductile iron are showing lower strength.

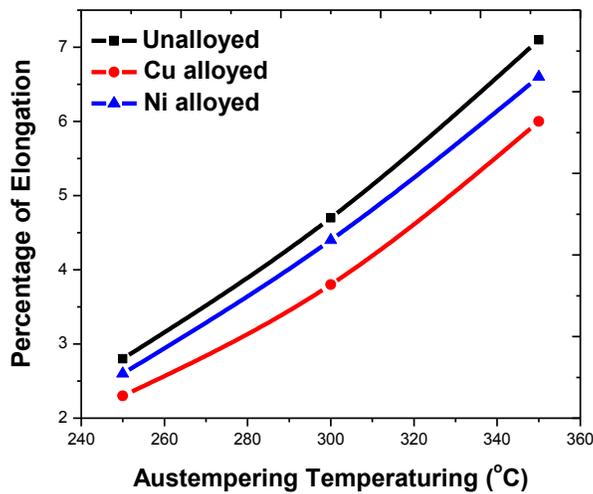## 5.1.5. Effect of austempering temperature on elongation

Fig. 5.17 Effect of austempering temperature on Elongation for 30 min

Figure 5.17is showing the variation of elongation with respect to the austempering temperature for 30 min. Elongation is increasing with respect to the austempering temperature in all the grades and un alloyed one showing higher ductility and Cu alloyed showing lower ductility.

Fig. 5.18 Effect of austempering temperature on Elongation for 60 min

Figure 5.18 is showing the variation of elongation with respect to the austempering temperature for 60 min. Elongation is increasing with respect to the austempering temperature in all the grades and Cu,Ni alloyed ductile iron almost showing same ductility at lower temperature and at higher temperature Cu alloyed showing lower ductility .

Fig. 5.19 Effect of austempering temperature on Elongation for 90 min

Figure 5.19 is showing the variation of elongation with respect to the austempering temperature for 90 min. Elongation is increasing with respect to the austempering temperature in all the grades and un alloyed one showing higher ductility and Cu alloyed showing lower ductility.

Fig. 5.20 Effect of austempering temperature on Elongation for 120 min

Figure 5.20 is showing the variation of elongation with respect to the austempering temperature for 120 min. Elongation is increasing with respect to the austempering temperature in all the grades and un alloyed one showing higher ductility and Cu alloyed showing lower ductility.
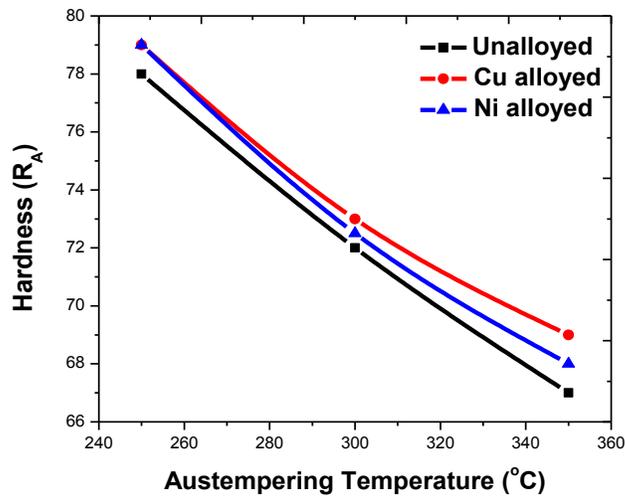
5.1.6. Effect of austempering temperature on hardness
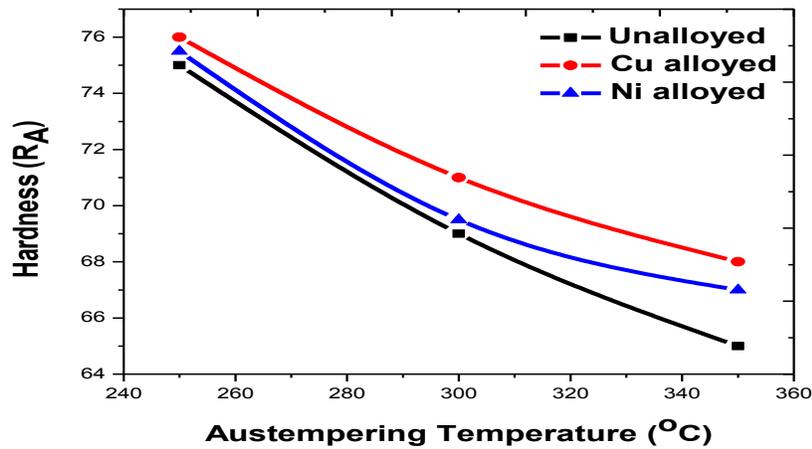
Fig. 5.21 Effect of temperature on hardness for 30 min

Fig. 5.21is showing the variation of hardness with respect to the austempering temperature for 30 minutes. . Hardness is decreasing with respect to the austempering temperature in all the grades. Cu alloyed showing higher hardness and un alloyed ductile iron showing lower hardness.
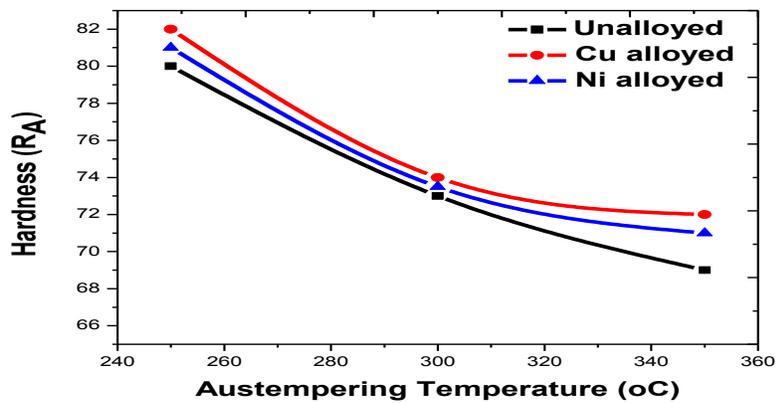
Fig. 5.22 Effect of temperature on hardness for 60 min

Fig. 5.22 is showing the variation of hardness with respect to the austempering temperature for 60 minutes. . Hardness is decreasing with respect to the austempering temperature in all the grades. Cu alloyed showing higher hardness and unalloyed ductile iron showing lower hardness.
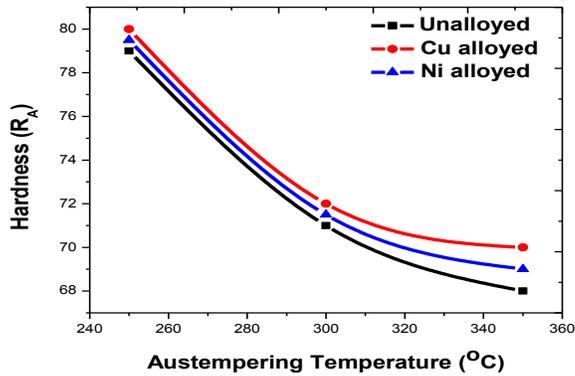
Fig. 5.23 Effect of temperature on hardness for 90 min

Fig. 5.23 is showing the variation of hardness with respect to the austempering temperature for 90 minutes. . Hardness is decreasing with respect to the austempering temperature in all the grades. Cu alloyed showing higher hardness and un alloyed ductile iron showing lower hardness. The difference in hardness among the grades is more at lower temperatures and high at higher temperatures.

Fig.5.24 Effect of temperature on hardness for 120 min

Fig. 5.24 is showing the variation of hardness with respect to the austempering temperature for 120 minutes. . Hardness is decreasing with respect to the austempering temperature in all the

grades. At lower temperatures Ni,Cu alloyed irons showing same hardness at lower temperature and Cu alloyed higher than the Ni alloyed.

5.2. X-ray diffraction analysis

5.2.1. Austempered ductile iron (Unalloyed)

The XRD patterns of austempered ductile iron (unalloyed), austempered at different temperatures and different timesare shown belowfigures.
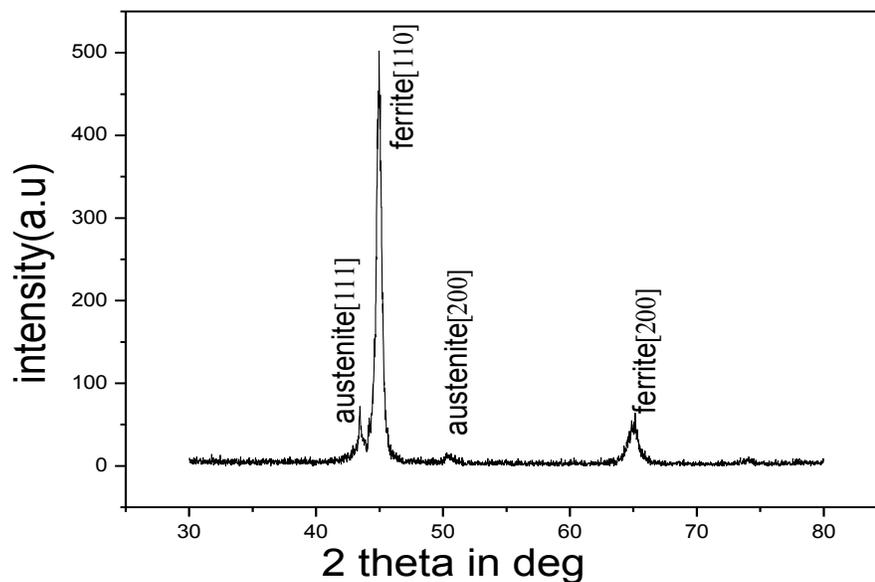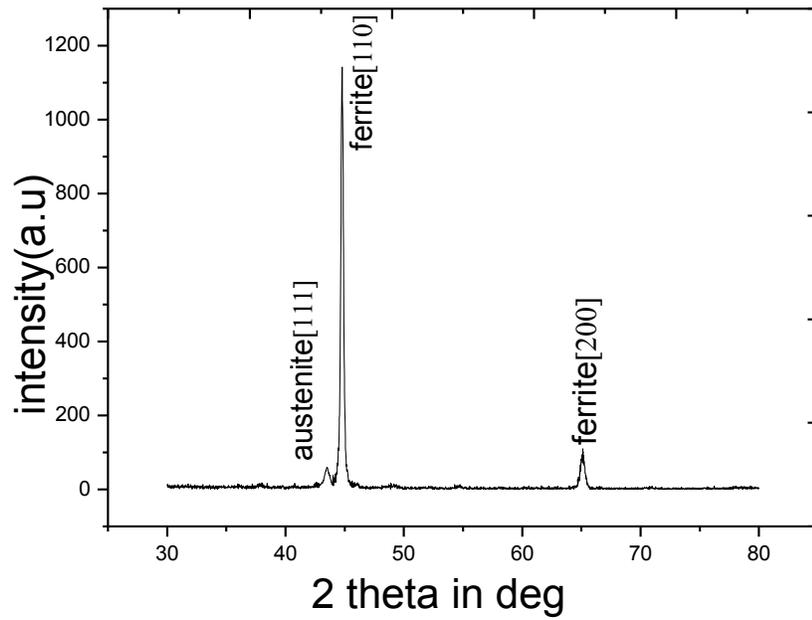
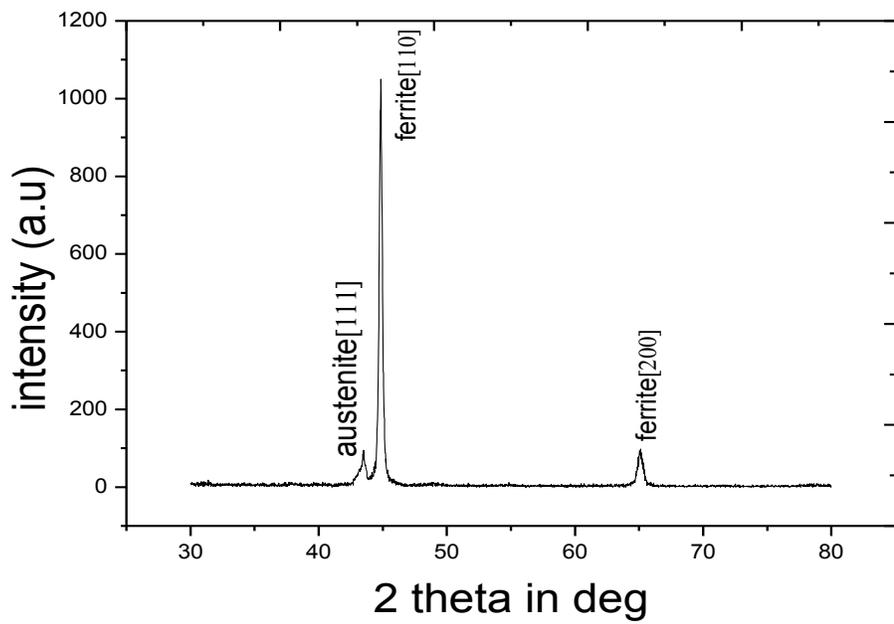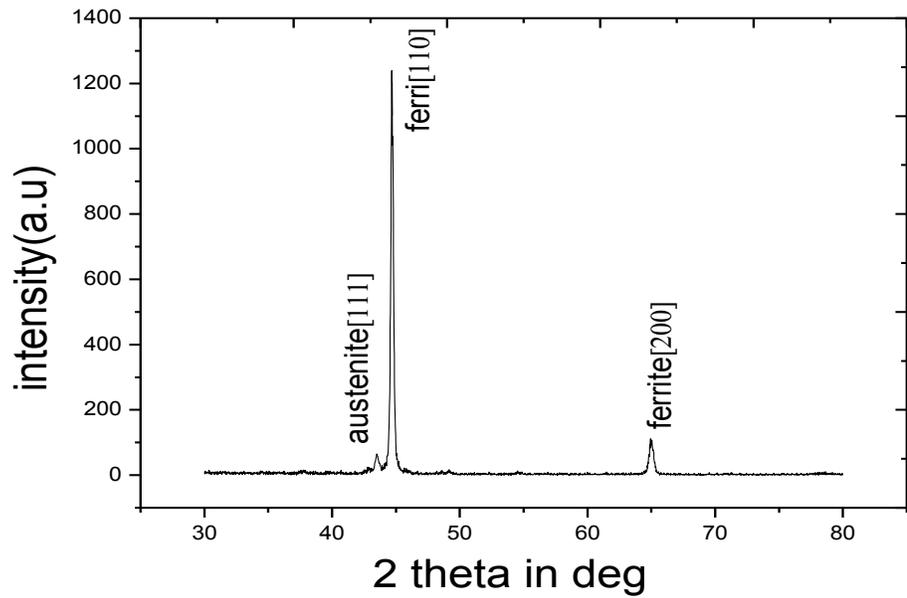Fig.5.25 XRD patterns of ductile ironsample austempered at 250°C for (a) 60 min and (b) for 90 min.

Fig.5.26 XRD patterns of ductile iron austempered (a) at 250°C for 120 min and (b) at 300^{0}C for 60 min.
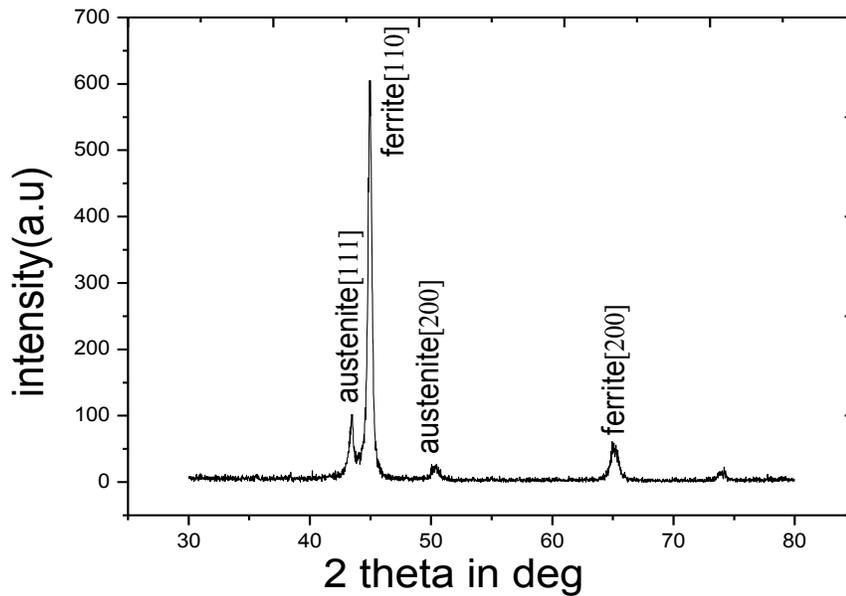
Fig.5.27 XRD pattern of ductile iron austempered at 350ᵒC for 60 min.

In the XRD pattern it is observed that the austenite (111) lines and ferrite (110) 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 increasing temperature.

5.2.2. Austempered ductile iron with copper
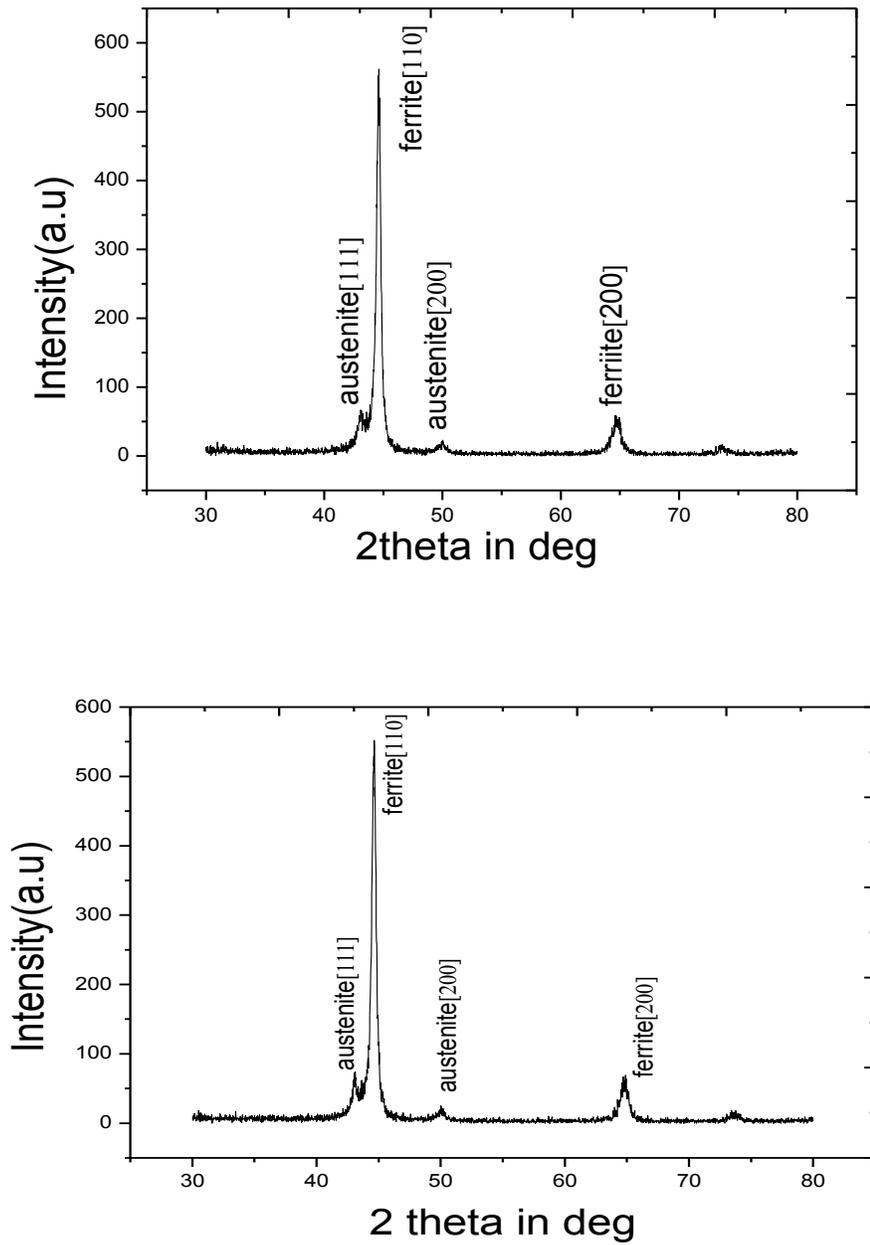
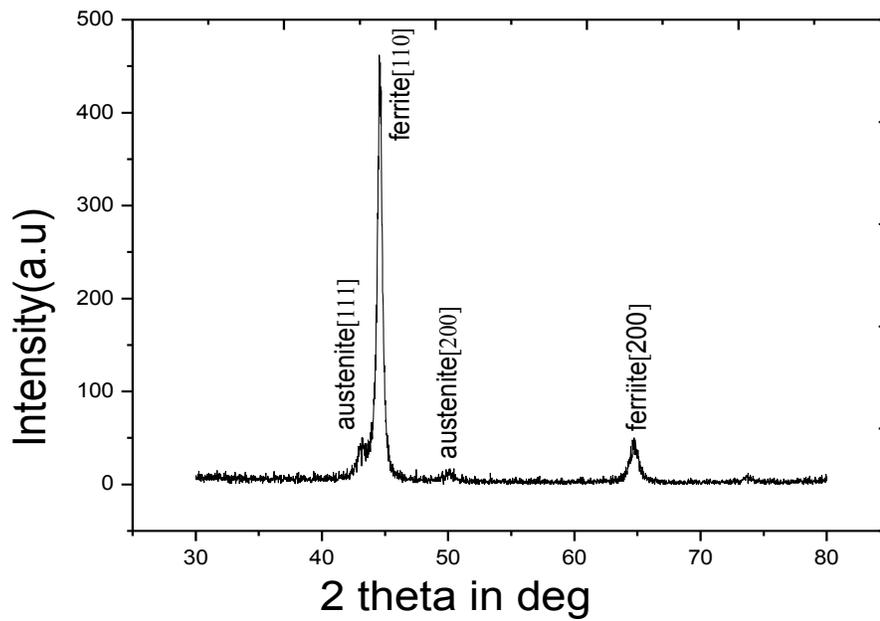Fig.5.28 XRD patterns of alloyed ductile iron austempered at 250°C for 60 min and 120min.
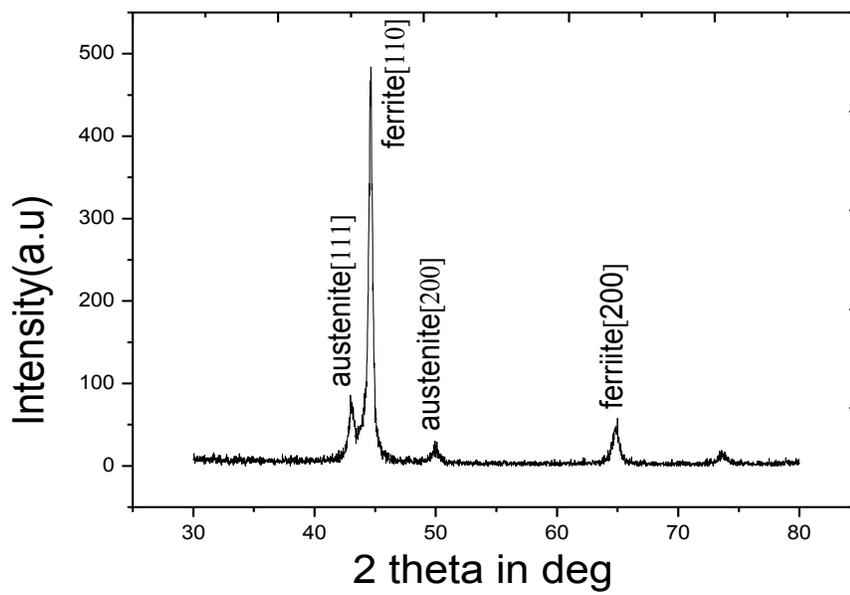
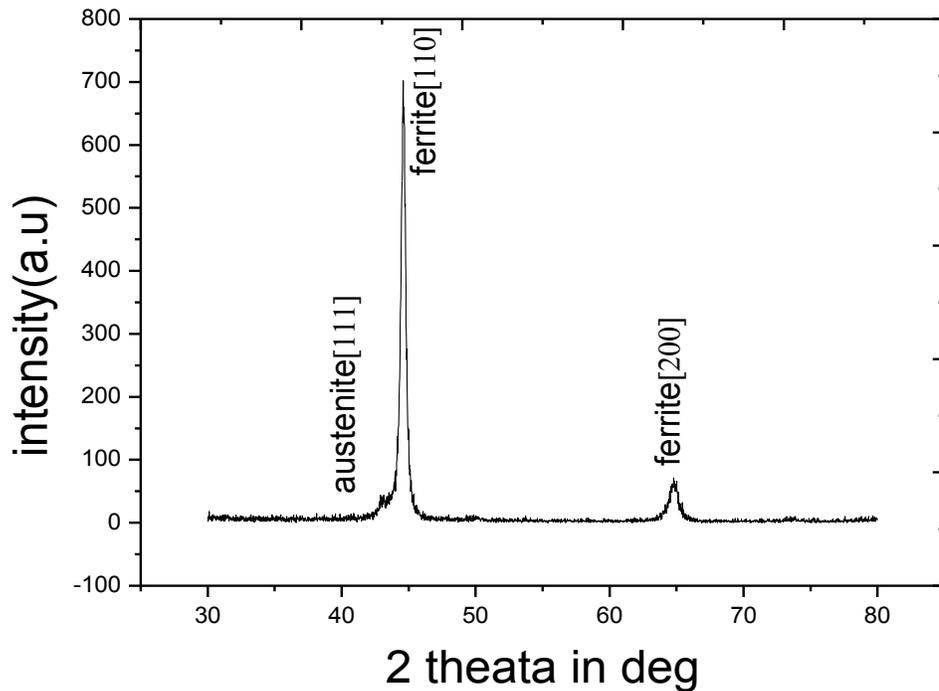Fig.5.29XRD patterns of alloyed ductile iron austempered at 250°C for 30 min and 350°C for 60 min.

Fig.5.30 XRD pattern of alloyed ductile iron austempered at 300°C for 60 min.

In the XRD pattern it is observed that the austenite (111) lines and ferrite (110) 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 increasing temperature.

5.3. Scanning electron microscopy

5.3.1. Microstructure

The microstructures of unalloyed and alloyed ductile iron samples were observed under the scanning electron microscope and are shown in following figures.
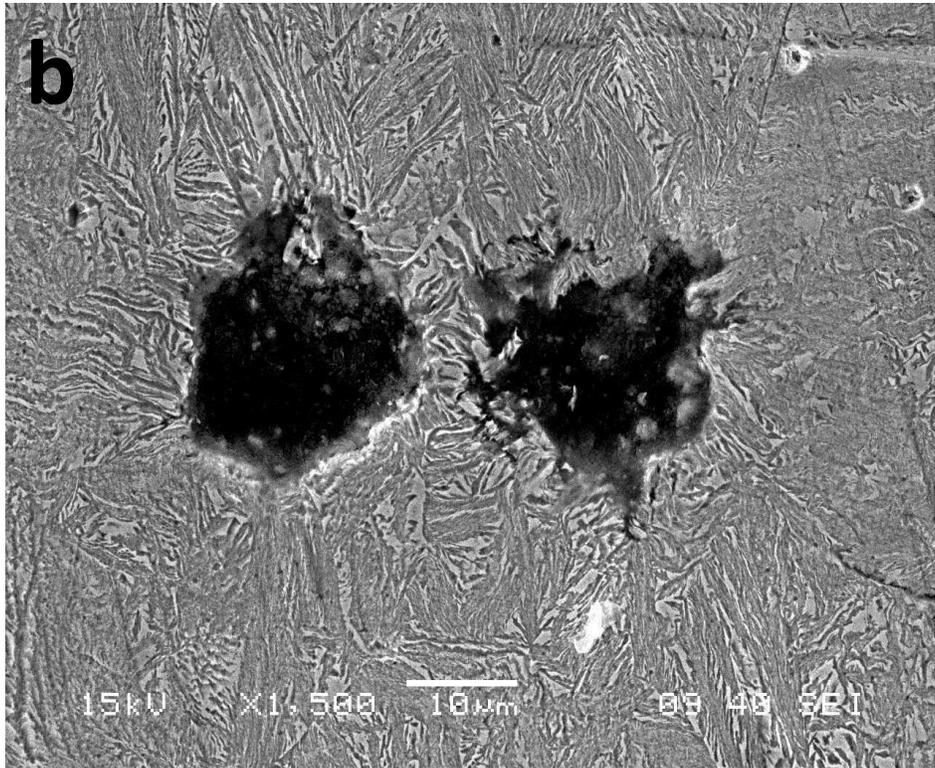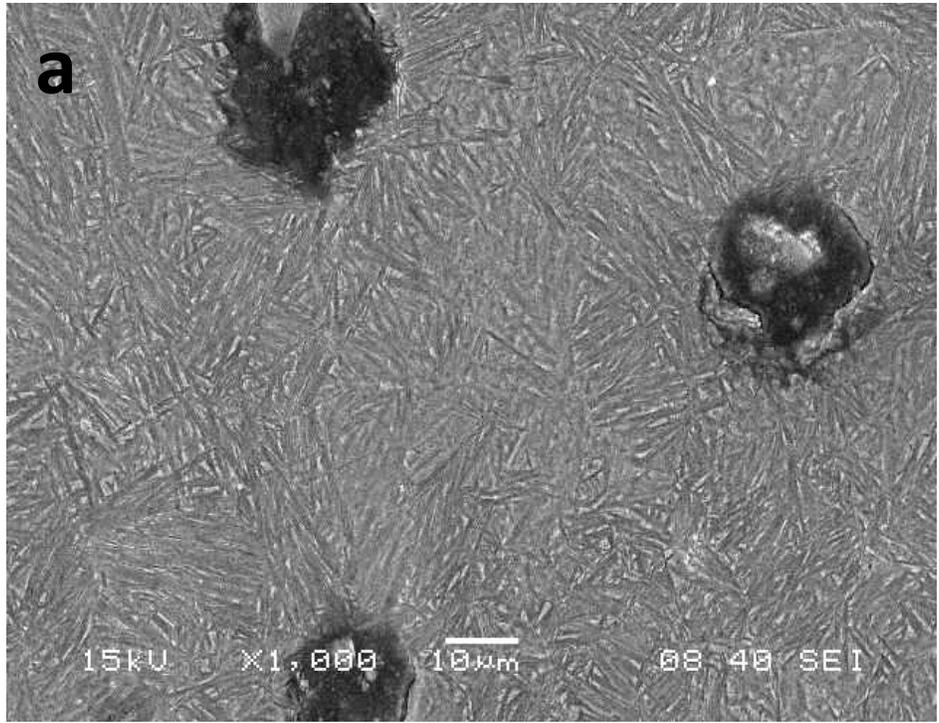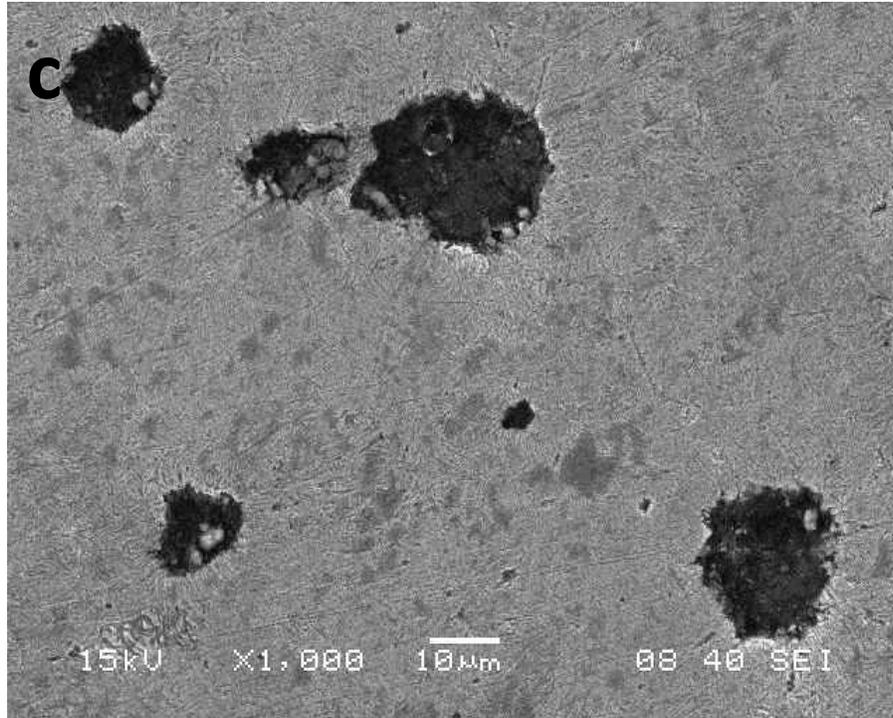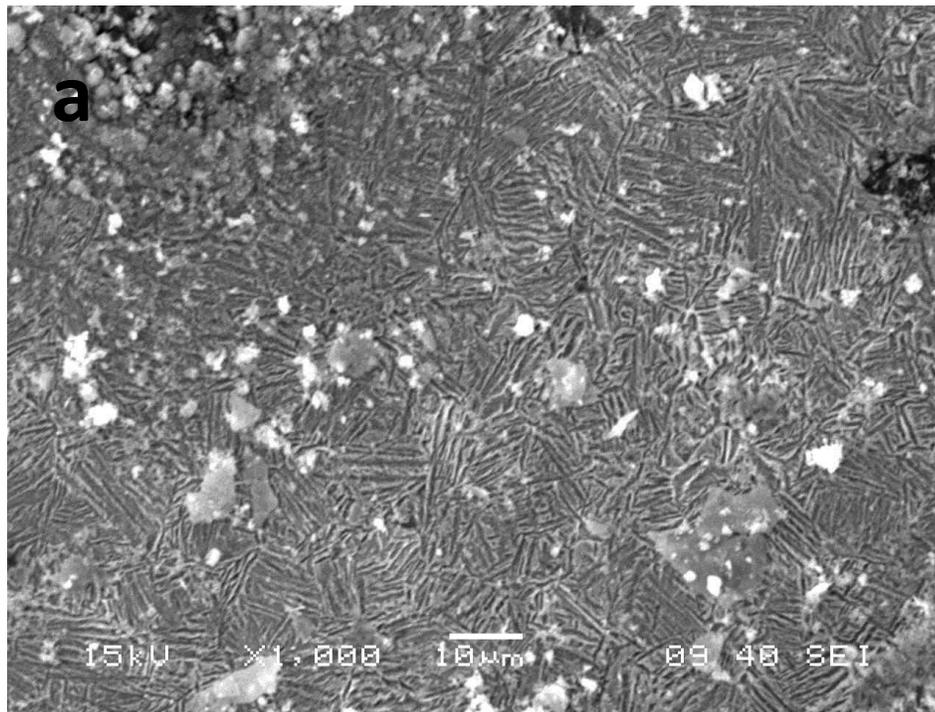
Fig. 5.31 Microstructure of the austempered ductile iron (unalloyed) austempered at (a) 250°C for 30 min (b) 350°C for 60 min (c) 300°C for 60 min
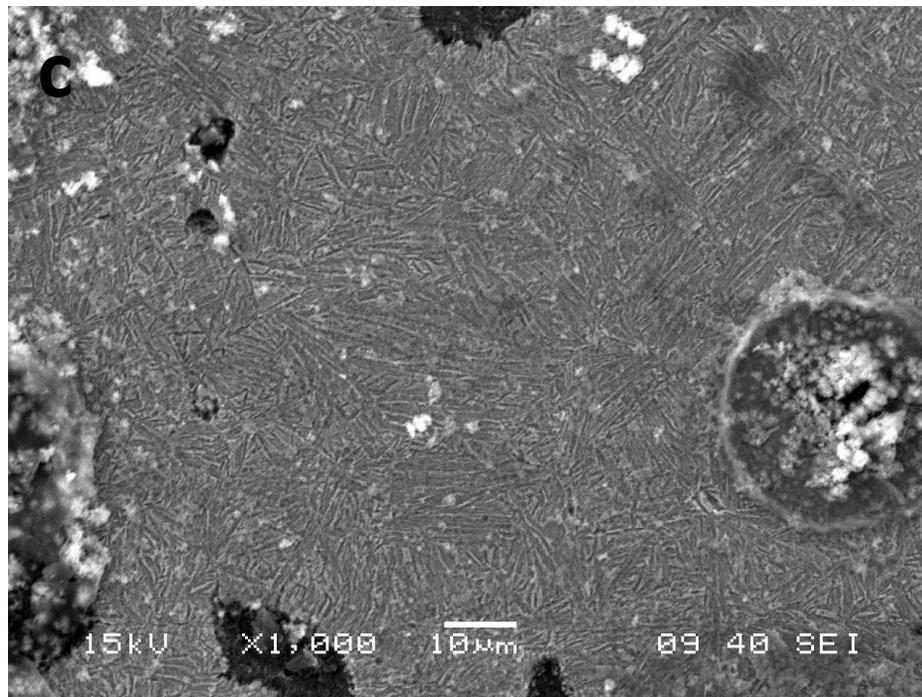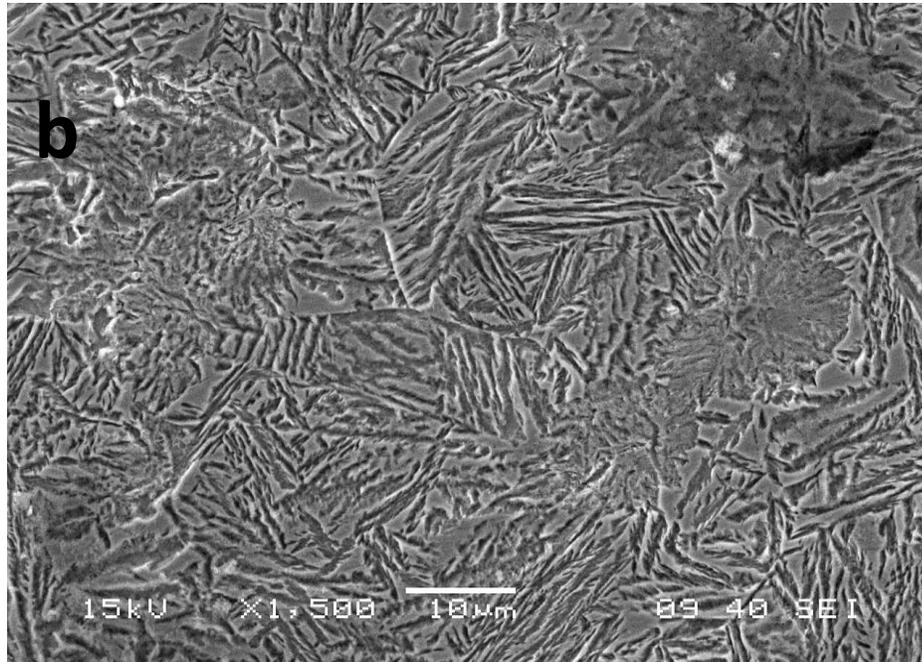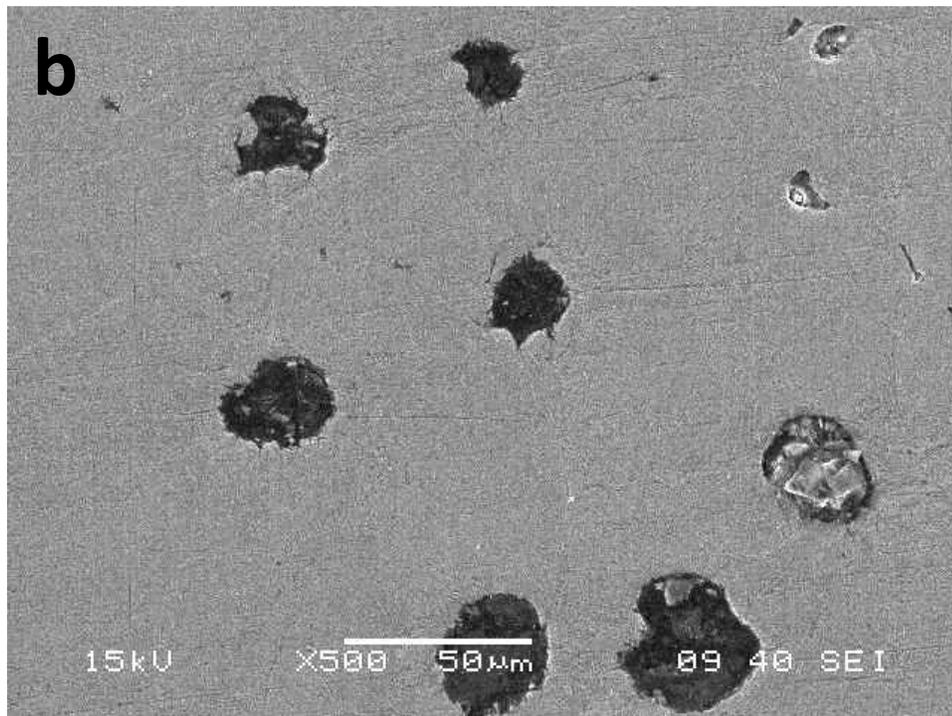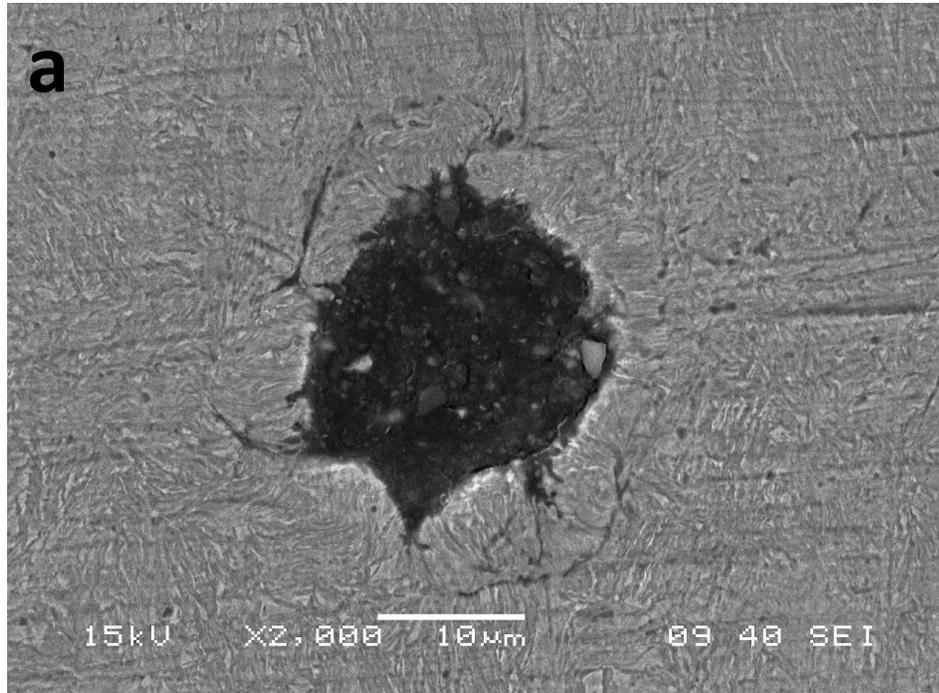
Fig.5.32 Microstructure of the austempered ductile iron (Copper alloyed) austempered at (a) 250°C for 60 min (b) 300°C for 60 min (c) 350°C for 60 min
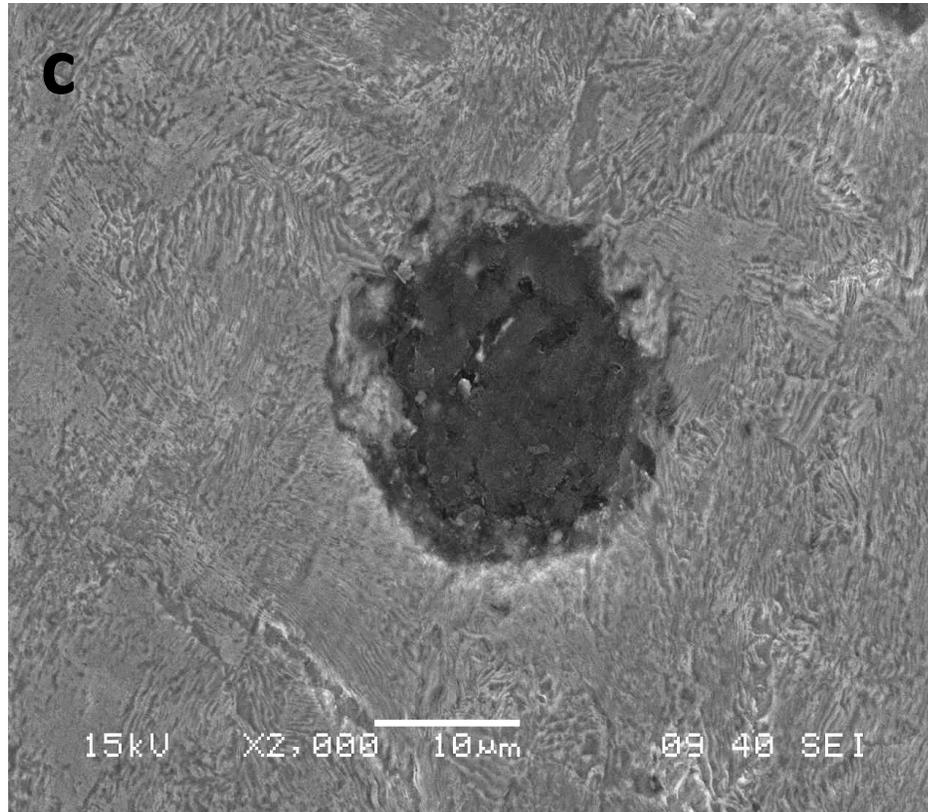
Fig.5.33 Microstructure of the austempered ductile iron (Nickel alloyed) austempered at
(a) 250°C for 60 min (b) 300°C for 60 min (c) 350°C for 60 min

In the above microstructure it is observed that the samples which are austempered at higher temperatures having upper bainitic structure and the samples which are austempered at lower temperatures are having lower bainitic structure. When the austempering temperature increasing the morphology of bainite also changing from acicular to plate like. The amount of retained austenite is increasing at higher temperature.At lower austempering temperatures the strength is higher. There is no significance difference between copper alloyed ductile iron and ductile iron without copper.

5.3.2. Fracrography

The morphology of fracture surfaces are analyzed by scanning electron microscopy and pictures are given bellow.
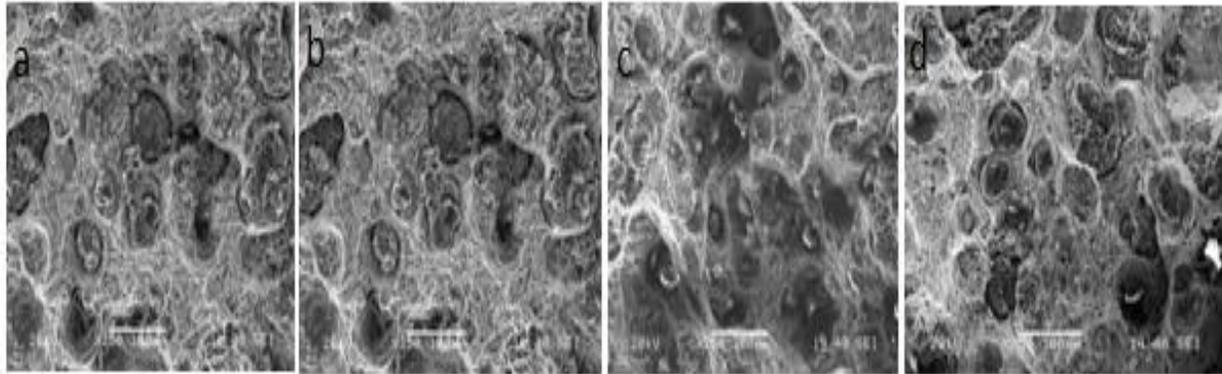
Fig. 5.34 Fracture surfaces of the copper alloyed ductile iron which is austempered at 250°C for (a) 30 min (b) 60 min (c) 60 min (d) 120 min
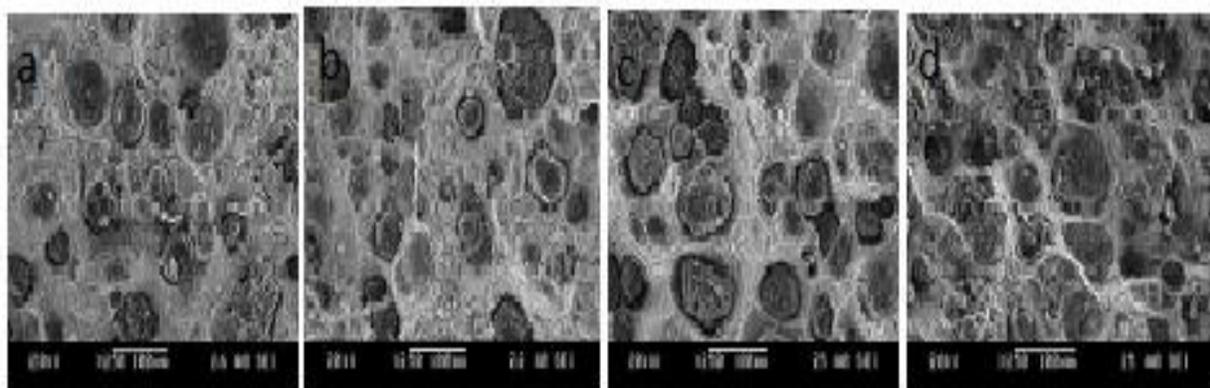
Fig.5.35 Fracture surfaces of theaustempered ductile (Unalloyed) which austempered at 250°C for (a) 30 min (b) 60 min, (c) 90 min and (d) 120 min

In the above pictures it is observed that, 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.It is observed that the dimple size increases but the number of dimples decreases with increasing austempering temperature. Dimple size increased with increasing austempering temperature, which indicates improvement in ductility.

Conclusions

The general trends, observed by analysing the results are that for constant austempering time, strength (both UTS and YS) and hardness decreases with the increase in temperature and ductility (which is represented by % elongation) increases with temperature.The effect of austempering parameters are pronounced on Y.S. rather than U.T.S.

The increase in ductility with the increase in austempering temperature is also supported by the study of microstructure and analysis of fractured surface as we find more amounts of austenite for the specimen's austempered at higher temperature. The percentage of ductile dimple in the fractured surface also increases with the increase in austempering time and temperature. These observations are true for all the grades of SG iron.

If we consider the effect of austempering time then we can see that for a constant temperature initially there is an increase in strength and hardness but after one hour (60 minutes) of austempering, both hardness and strength becomes constant or there may be a slight decrease in the value. As far as ductility is concerned, the property is improved with the austempering time however it becomes almost constant after a period of one and half hours (90 minutes). This is also true for all the grades.

However it has been observed that Cu and Ni have an effect on the rate of change in the values of the properties. From the results it is obvious that there is a sharp rise in strength when the austempering time is increased from 30 minutes to 60 minutes and this has happened for all the three temperatures used in the experiment but the percentage of increase in both UTS and YS is significantly higher for unalloyed one.

So by analysing the results we may draw the following conclusions.

- For a constant period of austempering, strength (both UTS & YS) and hardness decrease and ductility increases with the increase in temperature.

- For a particular austempering temperature, initially there is a sharp rise in the values of both strength and hardness with the increase in austempering time. After one hour of austempering, there is no significant increase in the values of these properties and there may be a slight decrease in strength. As far as ductility is concerned, the property is improved with time for a constant austempering temperature but it reaches a saturation point after a period of around 90 minutes (one and half hours).

- The increase in ductility with the time of austempering can be noticed in both microstructure and fractograph. The specimen's austempered at higher temperatures exhibit more amount of austenite in microstructure and increased percentage of ductile dimples in fractographs.

- Both Copper and Nickel play a significant role in the property development of austempered ductile iron (ADI). Both retard the rate of increase in strength and accelerate the rate of increase in ductility (% of elongation) to a considerable extent.The effect on ductility is more pronounced in case of Nickel.

- The alloying elements have a significant effect on the austempering process. Both of them retard the rate of decrease in strength with increasing temperature and accelerate the rate of increase in ductility(with austempering temperature)

- The effect of Copper appears to be more in case of strength. For examplethe decrease in the Y.S. for unalloyed S.G. iron is 32.20% when the austempering temperature is increased from 250^0C to 350^0 C keeping the time ofaustempering constant at 30 minutes. The decrease in Y.S. under similar conditions is 28.06% in case of Copper alloyed S.G. iron and 30.67% in case of Nickel alloyed ones.

- Both Copper and Nickel enhance the rate of increase in ductility due to austempering. In the present work the maximum increase in percentage of elongation for the unalloyed specimens has been found to be around 280% but for the alloyed ones it has been found to be more than 300%. In this regard the effect of Copper and Nickel are almost equal.

- Significantly more upper bainite was observed in the Ni-alloyed ADI than Cu-alloyed ADI.

Future scope of the work

Austempered ductile iron has found enormous applications in recent years due to the excellent combination of strength; ductility and wear resistance .It has started to replace steel in some structural applications.Engineering applications of ductile iron in as cast and different heat treated conditions are growing day by day. More research may be carried out for further improvement of the mechanical properties.In this regard the effect of both heat treatment process and alloying of elements have to be studied.

List of Research Publications:

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