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(Material Science)



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(M.Sc. Dissertation)

The Effect of Tempering Treatment on The Microstructure and Hardness of Austempered Ductile Iron (ADI)

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ABSTRACT

Nowadays, Austempered Ductile Iron (ADI) is a novel material exhibiting an excellent combination of mechanical properties which can be varied over a wide range by the correct choice of heat treatment process variables, as-cast structure and chemical composition.

Very little work was carried out on tempering of ADI alloys. The objective of this work is to study the effect of tempering treatment on the Microstructure and Hardness of Austempered Ductile Iron Alloyed with 1.6% copper and 1.6% nickel, as well as the effect of changing different parameters of heat treatment i.e. time and temperature on ADI .

In this study the ADI samples were tempered at different temperatures and times after austempering process (austenitised at 1000^{o}C for different times and austempered at 360^{o}C for 3 hours).

All samples were subjected to hardness testing and metallographic examination before and after heat treatment condition using conventional metallographic preparation techniques. It is important to note that all values given here are an average of at least 5 samples but in most cases, a larger number of tests. The sample results were compared before and after tempering.

In this study, the increase of the hardness value is gradually in the range of 300 to 500^{o}C with the appearance of highest values of hardenss in the range between 450^{o}C -500^{o}C. Then, there is a decline with a high rate in hardness beyond 500^{o}C. The value of hardness at 660^{o}C is very low compared to the one measured at low tempering temperature. Samples tempered at 660^{o}C show totally ferritic microstructure.

Also, It can be concluded that the effect of tempering time of ADI samples tempered at 450^{o}C for 90 , 120 and 150 minutes has slightly or no effect on the hardness values.

الملخص

في الوقت الحاضر، حديد الزهر المطيلي المطبع (ADI) مادة مبتكرة و التي تعرض خليط ممتاز من الخواص الميكانيكية التي يمكن أن يتم تغييرها على مدى واسع بالإختيار الصحيح لمتغيرات عملية المعالجة الحرارية و تركيبها الإبتدائي و محتواها الكيميائي.

تم إجراء عمل قليل جدا عن تطبيع معدن ADI. هدف هذا العمل هو دراسة تأثير معالجة التطبيع على التركيب المجهري و الصلادة لسبيكة ADI المسبوكة مع 1.6% نحاس و 1.6% نيكل ، بالإضافة إلى تغيير البارامترات المختلفة للمعالجة الحرارية و هما الوقت و درجة الحرارة على ADI.

في هذه الدراسة تم تطبيع عينات ADI في درجات حرارة و أزمنة مختلفة بعد عملية الأستمبرة ، (سخنت لدرجة 1000 درجة مئوية لعدة أزمنة و تمت الأستمبرة عند 360 درجة مئوية لمدة 3 ساعات).

كل العينات تم إخضاعها لقياس الصلادة و الفحص المجهري قبل و بعد المعالجة الحرارية و باستعمال تقنيات الإعداد المتعارف عليها للعينات. من المهم هنا ملاحظة أن كل القيم المعطاة على الأقل متوسط خمس عينات و قورنت النتائج قبل و بعد التطبيع.

في هذه الدراسة ،زيادة قيمة الصلادة بشكل تدريجي في مدى من 300 إلى 500 درجة مئوية يظهر القيم الأعلى للصلادة في مدى بين 400 و 500 درجة مئوية. ثم انخفاض بمعدل عالي في الصلادة ما بعد 500 درجة مئوية. إن قيم الصلادة في 660 درجة مئوية تكون منخفضة جدا مقارنة بالعينة المقاسة عند درجة حرارة تطبيع أقل. العينات المعالجة عند 660 درجة مئوية تظهر تركيب مجهري فريتي بشكل كامل.

أيضا يمكن أن يتم إستنتاج أن تأثير زمن التطبيع لعينات ADI عند 450 درجة مئوية لمدة 90، 120 و 150 دقيقة تقريبا ليس له تأثير على قيم الصلادة.

CHAPTER 1

INTRODUCTION

CHAPTER 1
INTRODUCTION

1.1 Introduction

The term, cast iron, refers a large family of ferrous alloys. Cast irons are primarily alloys of iron that contain more than 2.0 wt.% carbon. They also contain 1.0 to 3.0 wt.% silicon.

Changing carbon content, silicon content, besides alloying with various elements, and by varying melting, casting and heat treatment practice contol different properties.

Ductile Iron is referred to as **"**Nodular Iron**"** or Spheriodial graphite iron. After a decade of intensive development work in the 1950's, ductile iron had a phenomenal increase in the use as an engineering material during the 1960's, and since that it has been a rapid increase in its use in commercial applications. The mechanical properties of ductile irons are controlled primarily by the amount, distribution, and microstructures of matrix phases. Ductile iron properties can be improved by Austempering treatment, e.g. Austempered ductile iron (ADI).

Austempered ductile iron and even after 60 years of its discovery is still considered as a "new material". The main reason for that is the slow commercialization of the Austempering process. ADI remained a laboratory curiosity until 1972 when a limited facility was set up to process a small compressor crankshaft. However the first truly viable commercial service was delayed until introducing the new developed furnace. ADI has proved to be an excellent material as it possesses desirable properties such as, high strength, ductility, and toughness, combined with good wear resistance and machinability.

The mechanical properties of ductile iron and austempered ductile iron are determined by the metal matrix. In conventional ductile iron it is controlled by

the mixture of pearlite and ferrite. The mechanical properties of ADI are closely related to the selection of heat treatment parameters. During austempering, the austenite matrix of ductile iron undergoes a two-step reaction. In the first step austenite is transformed into ferrite and high carbon austenite, while in the second step the high carbon austenite decomposes into ferrite and carbide [1, 2].

Details of the terminology and structure of ADI have been described by Kovacs [3]. The morphology of ferrite austempered at higher temperature is feather-shape. Hence, for convenience this mixture structure and this ductile iron are called upper ausferrite and upper ADI, respectively. Similarly, that austempered at lower temperature are named lower ausferrite and lower ADI.

The processing window is also reduced by segregation of alloy additions, which causes the reaction rate to become faster in the eutectic cell and slower in the intercellular boundary. From an engineering point of view, it is obvious that the mechanical properties of ADI are very sensitive to austempering conditions and alloy additions, thus increasing the difficulty for successful production of ADI.

Tempering is one of the most important heat treatment processes that is applied to quenched steel and cast iron. The objectives of this process include reducing the brittleness of materials, improving toughness and ductility, and also, reducing the probability of cracking. Review of the relevant literature shows that the effect of tempering conditions (i.e. time and temperature) on the mechanical properties of most steel and cast iron has already been studied. However, there is no available report on the effect of tempering variables on mechanical properties whose results indicate that impact strength of the samples tempered at 600°C for 20 minutes, is better than those tempered at 200°C for 1 hour. The lack of published information on this subject can be due to the fact that this material has only recently been introduced.

1.2 Objective

The microstructure and mechanical properties of ADI dependant on the heat treatment conditions, chemical composition and as cast structure. The influence of austenitising conditions on the microstructure and mechanical properties of the alloy under investigation were studied by previous work carried out by Dr. Mohamed Alaalam [4-10]. very little work was carried out on Tempering of ADI alloys. But no literature was found on the effect of tempering treatment on the alloyed ADI contaning 1.6% copper and 1.6% nickel as the main alloying elements has been investigated, therefore the prime objective of this research work is to study the effect of tempering treatment upon the microstructure and hardnes properties of this particular alloy.

This research is devided into six chapters. chapters 1 and 2 introduce the introduction and background and chapter 3 shows the experimental procedures used to examine the effect of tempering conditions on the mechanical properties and microstructure of ADI. Results, discussion and conclusions are presented in chapters 4, 5 and 6 respectively.

CHAPTER 2
LITERATURE REVIEW

CHAPTER 2
BACKGROUND

The aim of this chapter is to provide a background to austempered ductile irons and the characteristics of this material which are important in understanding the subject.

2.1 CAST IRON

The term, cast iron, identifies a large family of ferrous alloys. Cast irons are primarily alloys of iron that contain more than 2.0 wt. % carbon. They also contain 1.0 to 3.0 wt. % silicon. The different properties of castings can be achieved by changing carbon content, silicon content, by alloying with various elements, and by varying melting, casting and heat treatment practice. Cast irons, as the name implies, are indeed to be cast to shape rather than formed in solid state. Cast irons have low melting temperatures and are very fluid when melted and have undergone slight to moderate shrinkage during solidification. However, cast irons have relatively low impact resistance and ductility, which limits their use [11]. This must be taken into account when designing castings to withstand service stresses.

2.2 TYPES OF CAST IRONS

Cast irons generally contain more than 2% C and a variety of alloying elements. These are generally classified by a rather simple and archaic system. Classification is done on the basis of the appearance of their fracture surface, their microstructure and properties. There has been two classes of cast irons historically, one having a gray fracture appearance and other having a white fracture appearance, named as *gray cast iron* and *white cast iron* respectively.

Those irons having both gray and white appearances are called *mottled iron.* It is interesting to note that these names are still apply today. Over the years, other cast irons have been evolved which have their names derived from their mechanical properties, such as *malleable iron* and *ductile iron*. More recently *compacted graphite iron* and *austempered ductile iron* have been introduced.

There are five factors which lead to the different types of cast irons namely, the carbon content, the alloy, the impurity content, the cooling rate and the heat treatment after casting. These parameters control the composition as well as the form of parent matrix phase present [12].

Therefore, cast irons can be broadly classified into the following categories:

2.2.1 Gray cast irons:

It is the most common type of cast iron, it has a gray fracture surface due to high volume of graphite *flakes.* Carbon in graphite form is more stable than carbide form.

During cooling if it is subjected to a controlled cooling rate and adequate alloying addition then carbon gets precipitated out as graphite flakes. It has high Si content because it promotes the formation of graphite during solidification. Gray cast irons have negligible ductility but are useful because they can be easily casted to complex shapes and are inexpensive. These also have very low impact resistance.

2.2.2 White cast iron:

Rapid solidification of gray iron results in white cast iron. It has a white fracture surface.

Graphite flakes are not presented in this type of cast irons, an iron carbide network is presented, and that gives a white fracture surface. The Si content is lower to minimize the graphitizing effect. They are hard and have excellent abrasion resistance, but they also have excessive brittleness and poor machinability. To enhance wear resistance generally Mo, Cr, Ni are added to it.

2.2.3 Mottled iron:

This type of cast iron is not intentionally produced and results from a transition between gray and white cast irons. It is not necessarily a desirable material.

2.2.4 Malleable cast iron:

It is produced by heat treatment of white cast iron in which the iron carbide network decomposes or breaks down into *temper carbon*. This process is called malleablization which involves two stages of annealing. Because of the absence of hard and brittle carbide phase, iron becomes malleable. Disadvantage of this type of cast iron is its limited section thickness and prolonged annealing cycles.

2.2.5 Spheroidal graphite cast iron or ductile iron:

It is produced by adopting special alloy addition and proper cooling rates so that the carbon can be converted to spherical forms which can be used in those fields where carbon in the flake form or the temper form cannot be used. The nodules are formed during solidification and not during heat treatment. It can be of three types namely, ferritic, pearlitic/ferritic, martensitic. It has excellent mechanical properties compared to steels. There is a subclass of ductile iron named as **Austempered ductile iron**. It has the same nodular or spherical graphite as in ductile iron but the matrix is a combination of bainite and stabilized austenite. Austempering is necessary for this type of cast iron structure to be obtained.

Here graphite is present in compact form, and shape of graphite is controlled by minor alloying addition. Austemperd ductile irons have excellent mechanical properties such as tensile strength, ductility and wear resistance [6].

2.3 DUCTILE IRON

Ductile iron derives its name from the fact that, in the as-cast form, it exhibits measurable ductility. By contrast, neither white iron nor grey iron exhibits significant ductility in a standard tensile specimen [11].

Ductile iron is defined as a high carbon containing, iron-base alloy in which graphite is present in a compact, spheroidal shape [13].
Ductile Iron is also referred to as " Nodular Iron " or Spheriodial graphite iron and it was patented in 1948. After a decade of intensive development work in the 1950's, ductile iron had a phenomenal increase in the use as an engineering material during the 1960's, and there has been a rapid increase in its use in commercial applications since [14].

An unusual combination of properties is obtained in ductile iron because the graphite occurs as spheroids rather than as graphite flakes as in grey iron. This mode of solidification is obtained by adding a very small, but specific amount of Mg & Ce or both to molten iron of proper composition. The base iron is severely restricted in the allowable contents of certain minor elements that can interfere with graphite spheroid formation. The added Mg reacts with S or O in the melt or molten iron and the way the graphite is formed. Control procedures have been developed to make the processing of ductile iron dependable [14].

The high carbon & silicon content of ductile iron provide the casting process advantageous, but the graphite nodules have only the nominal influence on the mechanical properties of the melt. Ductile iron, like malleable iron, exhibits a linear stress- strain ratio, a considerable range of yield strengths

and as its name implies, ductility. Castings are made in a wide range of sizes with sections which are very thin or very thick [15].

The different grades are produced by controlling the matrix structure around the graphite either as cast or by subsequent heat treatment. Only minor compositional differences exist among the regular grades, and these adjustments are made to promote the desired matrix microstructures. Alloy addition may be made to abet in controlling the matrix structure as cast to provide response to heat treatment. Special analysis of ductile iron and high alloy ductile irons provide unusual properties for special application. [14, 16]

2.3.1 History of Ductile Iron

Foundry men continued to search for an ideal cast iron as cast “grey iron” with mechanical properties equal or superior to malleable iron. In 1943, Keith Dwight Mills made a ladle addition of Magnesium (as copper-magnesium alloy) to cast iron in the International Nickel Company Research Laboratory. The solidified castings contained no flakes but nearly perfect spheres of graphite [17].

Five years later, at 1948 AFS Convention, Henton Morrogh of British Cast Iron Research Association announced the successful production of spheroidal graphite in hyper eutectic grey iron by addition of small amount of cerium [11].

At the same time Morrogh from the International Nickel Company, presented a paper which revealed the development of magnesium as graphite spheroidizer. On October 25, 1949, patent 2,486,760 was granted to the International Nickel Company, assigned to Keith D. Mills [17], Albert P. Gegnebin and Norman B. Pilling. This was the official birth of ductile iron.
Worldwide growth of ductile iron as shown in figure 2.1

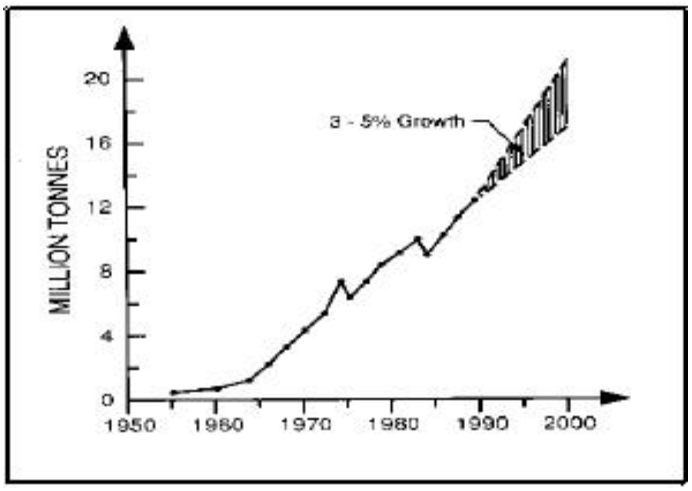


Fig. 2.1: worldwide growth of ductile iron [17].

Various grade of S.G. irons accepted as per international norms are given in Table 2.1[18]:

Table 2.1 :Grads of S.G Irons [International standard ISO 1083: 1987]

grade	Tensile strength (N/mm^2)	0.2% Proof strength (N/mm^2)	Elongation (%)
900-2	900	600	2
800-2	800	480	2
700-2	700	420	2
600-3	600	370	3
500-7	500	320	7
450-10	450	310	10
400-15	400	250	15
400-18	400	250	18
400-18L	400	250	18
350-22	350	220	22
350-22L	350	220	22

2.3.2 Chemical Composition:

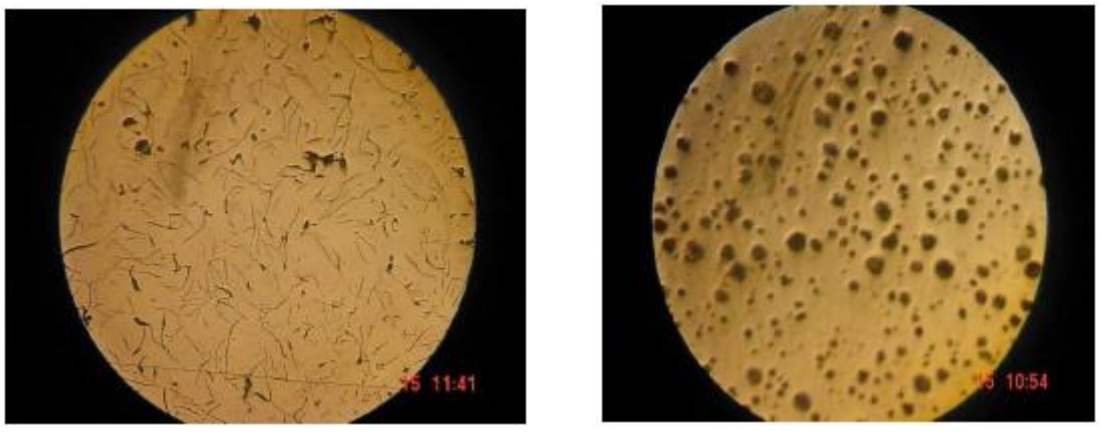
Chemically this material is same as gray iron and is Fe-C-Si alloy. It led to the development of cast iron technology since 1948. As the name suggests, it was developed to overcome the brittle nature of gray and white irons. It is quite ductile in as-cast form and negates the need for long heat treatments such as those required to produce malleable iron [19].

2.3.3 Microstructure:

Engineering applications of cast iron have been traditionally based upon gray (Flake graphite) irons providing a range of tensile strengths between about 150 N/mm^2 and 400 N/mm^2 with recommended design stresses in tensile applications of 0.25 × tensile strength. Despite their limited strength gray irons provided very useful combinations of properties, which have ensured there wide continuing use. In fact gray irons are still account for nearly 70% of all iron castings produced. In contrast ductile irons have tensile strengths ranging from 350 to 1500 N/mm^2 with good elongation and high toughness. They now account for about 25% of iron casting production serving in safety critical applications where they have replaced steel casting, forging and fabrications with technical and cost advantage [19].

The main difference between ductile iron and gray iron is the morphology of graphite particles as shown in figure 2.2 which take on a nodular or almost spherical form after suitable treatments are made to the melt. The major microstructural constituents of ductile iron are: the chemical and morphological forms taken by carbon, and the continuous metal matrix in which the carbon and/or carbides are dispersed [19].

The important micro-structural components of ductile iron are defined in figure 2.2 as following :-

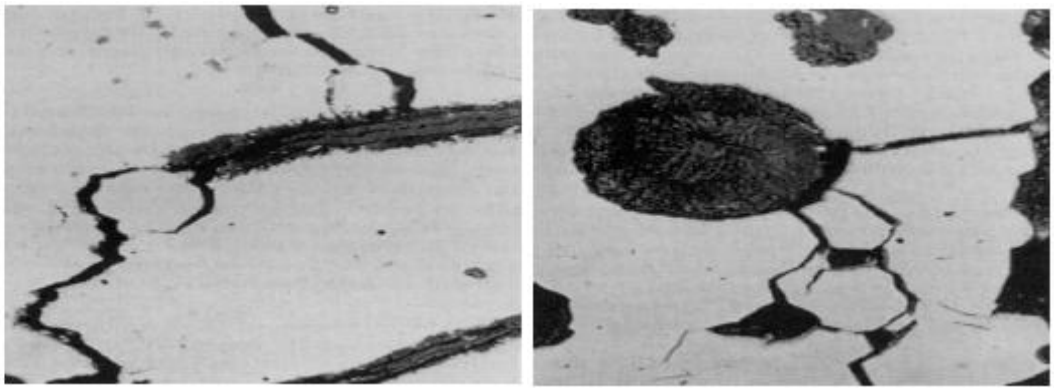


(a) (b)

Fig. 2.2: Microstructure of (a) gray and (b) ductile iron[19].

- **Graphite**

This is the stable form of pure carbon in cast iron. Its important physical properties are low density, low hardness and high thermal conductivity and lubricity. Graphite shape, which can range from flake to spherical, plays a significant role in determining the mechanical properties of cast irons. Figures 2.3 (a) and (b) show that graphite flakes acting like cracks in the iron matrix, while graphite spheroids act like "crack arresters", giving the respective irons dramatically different mechanical properties [20].



(a) (b)

Fig. 2.3: Graphite (a) flakes and (b) nodules[20].

- **Carbide:**

Carbide, or cementite, is an extremely hard, brittle compound of carbon with either iron or strong carbide forming elements, such as chromium, vanadium or molybdenum. Massive carbides increase the wear resistance of cast iron, but make it brittle and very difficult to machine. Dispersed carbides in either lamellar or spherical forms play an important role in providing strength and wear resistance in as-cast pearlitic and heat-treated irons [20].

- **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 accicular ferrite provides an exceptional combination of high strength with good ductility and toughness [20].

- **Bainite:**

Bainite is a mixture of ferrite and carbide, which is produced by alloying or heat treatment [20].

- **Pearlite:**

Pearlite, produced by an 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 [20].

- **Martensite:**

Martensite is a supersaturated solid solution of carbon in iron produced by rapid cooling. In the untempered condition it is very hard and brittle. Martensite is normally "tempered" - heat treated to reduce its carbon by the precipitation of carbides - to provide a controlled combination of high strength and wear resistance [20].

- **Austenite:**

Normally, a high temperature phase consisting of carbon dissolved in iron, it can exist at room temperature in austenitic and austempered cast irons. In austenitic irons, austenite is stabilized by nickel in the range 18-36%. In austempered irons, austenite is produced by a combination of rapid cooling which suppresses the formation of pearlite and the supersaturation of carbon during austempering, which depresses the start of the austenite to- martensite transformation far below room temperature. In austenitic irons, the austenite matrix provides ductility and toughness at all temperatures, corrosion resistance and good high temperature properties, especially under thermal cycling conditions. In austempered Ductile Iron stabilized austenite, in volume fractions up to 40% in lower strength grades, improves toughness and ductility and responses to surface treatments such as fillet rolling [20].

2.3.4 Family of Ductile Irons:

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

2.3.4.1 Austenitic Ductile Iron:

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

2.3.4.2 Ferritic Ductile Iron:

Graphite spheroids in a matrix of ferrite provide an iron with good ductility and resistance and with a tensile and yield strength equivalent to low carbon steel. Ferritic Ductile Iron can be produced "as-cast" but may be given an annealing heat treatment to assure maximum ductility and low temperature toughness.
Ferritic ductile iron microstructure is shown in Figure 2.4.

2.3.4.3 Ferritic Pearlitic Ductile Iron:

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

2.3.4.4 Pearlitic Ductile Iron:

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

used in the as-cast condition, but Ductile Iron can also be alloyed and/or heat treated to provide the following grades for a wide variety of additional applications [20]. Pearlitic ductile iron microstructure are shown in Figure 2.5

2.3.4.5 Martensitic Ductile Iron:

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

2.3.4.6 Bainitic Ductile Iron:

This grade can be obtained through alloying and/or by heat treatment to produce a hard, wear resistant material [20].

2.3.4.7 Austempered Ductile Iron (ADI):

ADI, the most recent addition to the Ductile Iron family, is a sub-group of Ductile Irons produced by giving conventional Ductile Iron a special austempering heat treatment. Nearly twice as strong as pearlitic Ductile Iron, ADI still retains high elongation and toughness. This combination provides a material with superior wear resistance and fatigue strength [20].
Austemperd ductile iron microstructure is shown in Figure 2.6.

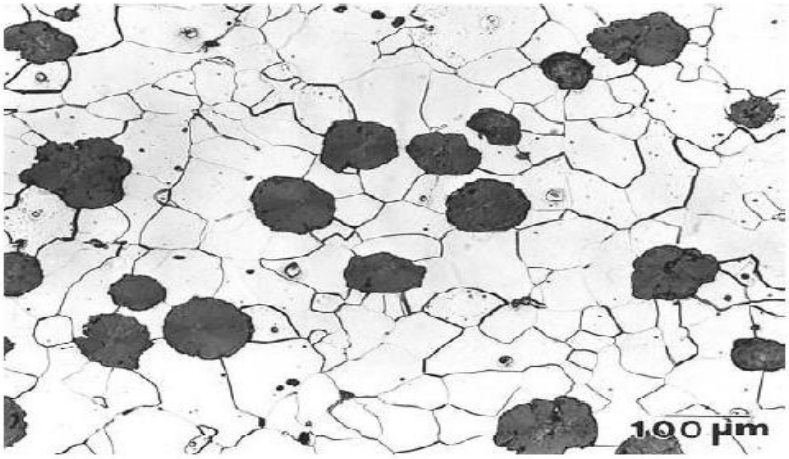


Fig. 2.4: Ferritic ductile iron microstructure [12].

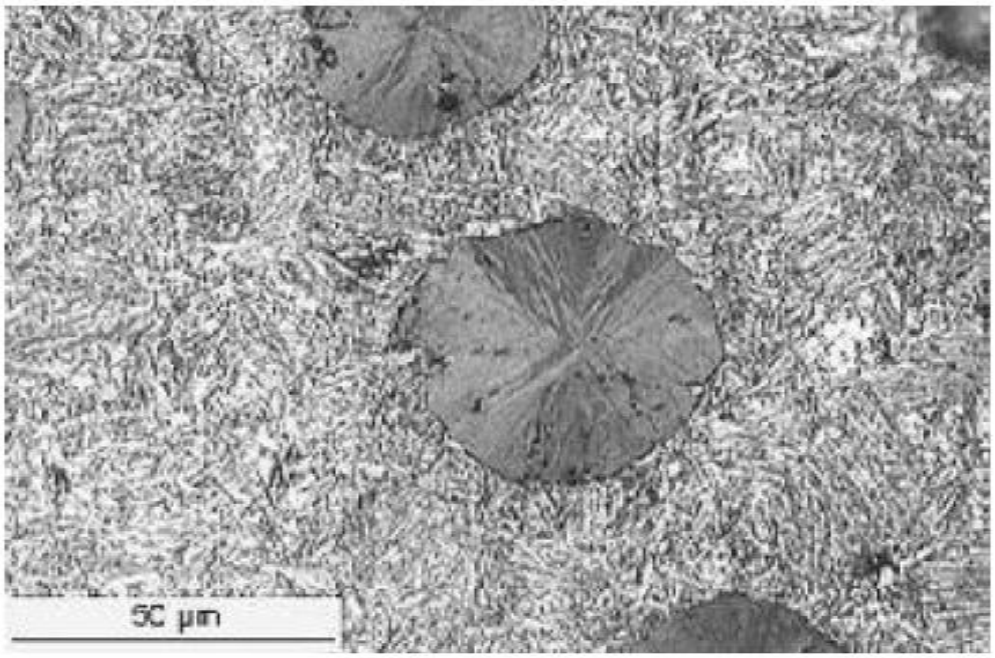


Fig. 2.5: Pearlitic ductile iron microstructure [12].

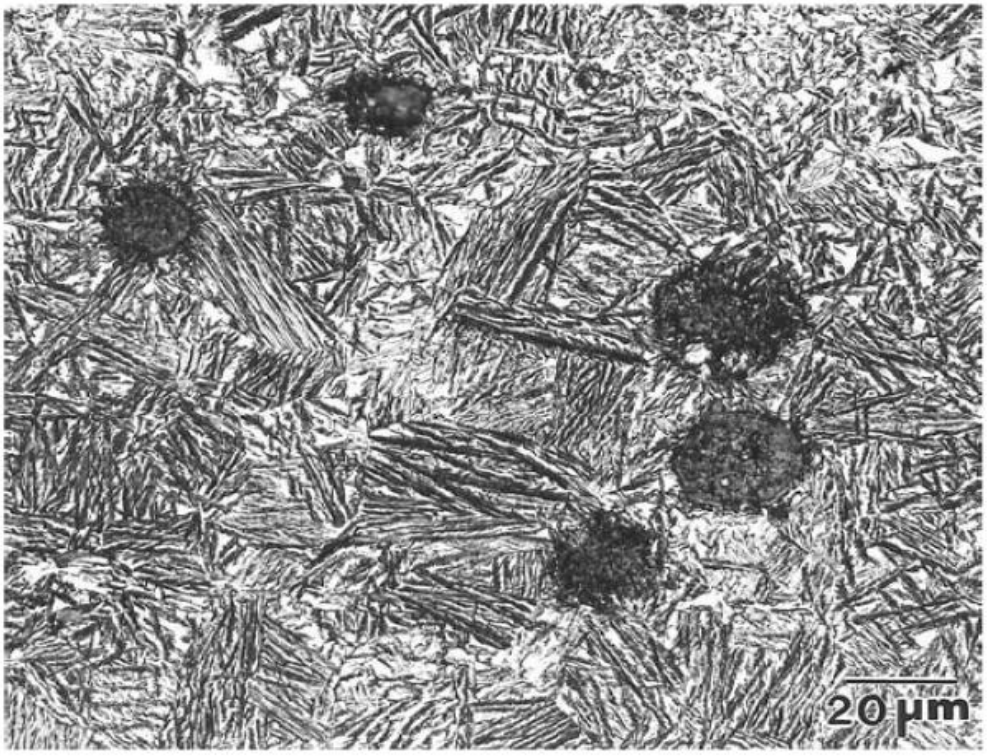


Fig. 2.6: Austemperd ductile iron microstructure [12].

2.3.5 Production of Ductile Iron

Ductile iron can be produced by treating low sulphur liquid cast iron with an additive usually containing magnesium and then inoculated just before or during casting with a silicon-containing alloy.

2.3.5.1 Raw Materials

To produce ductile iron with the best combination of strength and toughness, raw materials must be chosen which have lower than 0.02 wt% sulphur and are low in trace elements. Low manganese content is also needed to achieve as-cast ductility. Higher strength grades of ductile iron can also be made with common grades of constructional steel scrap, pig iron and foundry returns, but certain trace elements e.g. lead, antimony and titanium are usually kept as low as possible to achieve good graphite structure.

2.3.5.2 Control of the Composition of Ductile Iron

The composition of unalloyed ductile iron is similar to that of grey iron with respect to carbon and silicon contents. Carbon contents of unalloyed ductile iron ranges from 3.0wt.% to 4.0wt.% and silicon content from 1.6 wt% to 2.8 wt%. The sulphur and phosphorus levels of high quality ductile iron, however, must be kept very low at 0.03 wt.% S maximum and 0.1 wt.% P maximum, which are ten times lower than the maximum levels for grey cast iron. Other impurities must also be kept low because they interfere with formation of graphite nodules in ductile iron [21].

All the elements in the composition of ductile iron should be controlled. The following are the important elements in the production of ductile iron [22].

Total Carbon

The optimum range of carbon is usually 3.4 to 3.8 wt.% depending on the silicon content. Above this range there is a danger of graphite floatation, especially in heavy sections.

Silicon

Silicon enters ductile iron from raw materials, including cast iron scrap, pig iron, ferro-alloys and to small extent from silicon-containing alloys during inoculation. The preferred range is about 2.0 to 2.8 wt.%. Lower silicon levels lead to high ductility in heat-treated iron but there is danger of carbides in thin sections. High silicon helps to avoid carbides in thin sections. It also increases hardness and tensile strength.

Carbon Equivalent

The carbon, silicon and phosphorus contents can be considered together as a Carbon Equivalent Value. This is a useful guide to foundry behavior. There are several Carbon Equivalent formulas and they are useful in assessing the casting properties. The formula that is commonly used is as follows:

$$CE = C\% + 1/3(\%Si + \%P) \text{ [12]}$$

If the value CE is equal to 4.3wt.%, the iron will be wholly of eutectic composition. When CE is lower than 4.3, there will be a proportion of dendrites; if CE is higher than 4.3 wt.% there will be primary graphite nodules in the structure.

Manganese

The main source of manganese is steel scrap used in the charge. Manganese should be limited in order to obtain maximum ductility. In as- cast ferrite iron, it should be 0.2 wt. % or less. Manganese produces undesirable micro segregation especially in heavy section. It encourages the formation of grain-boundary carbides which promote low ductility, low toughness and persistent pearlite.

Magnesium

The magnesium content which is required to produce spheroidal graphite usually ranges from 0.04 to 0.06 wt.%. If the initial sulphur content is below 0.015 wt.%, lower magnesium content in the range of 0.035 to 0.04 wt.% may be satisfactory. Compacted graphite structure with inferior properties may be produced if magnesium is low, while too high magnesium content may promote dross defects and carbide formation.

Minor Elements Promoting Non-spheroidal Graphite

Lead, antimony, bismuth and titanium are undesirable elements that may be introduced in trace amount with raw materials in the charge. Their effects can be neutralized by cerium addition as reported by I. C. Hughes [22].

Aluminium

The presence of even trace amount of aluminium in ductile iron may promote surface pinhole-porosity and dross formation. The common source of aluminium is contaminants in steel and cast-iron scrap. Another source is aluminium containing inoculants so use of inoculants of low aluminium is advisable. Aluminium as low as 0.01 wt.% may cause pinholes in ductile iron.

Phosphorus

Phosphorus is normally kept below 0.05% because it promotes unsoundness and lowers ductility.

Minor Elements Promoting Carbides

Chromium, vanadium and boron are carbide promoters. They are controlled by a careful selection of metallic raw materials for melting.

2.3.5.3 Charge Materials

The metallic charge for ductile iron base consists mainly of: Pig iron, steel scrap, return ductile iron scrap and ferroalloys [13].

Pig Iron

The ideal pig iron for ductile iron charge is pure iron-carbon alloy, which is not available. It is believed that sorel metal is the best charge. In sorel metal the manganese content is very low i.e. 0.009 wt.% and its content of elements which either promote carbides or interfere with spheroidization of graphite is low.

Steel Scrap

Steel scrap is an important component of ductile iron charge. Chemical composition and physical shape are to be considered. The physical shape includes dimensions and specific surface. All melting equipment has its limitations as to maximum size. The cupola furnace also has a minimum size limitation.

Even though very small pieces may be charged into electric induction or arc furnaces (such as thin plate chippings) these have very large specific surface areas which rust rapidly. Even though rust is not believed to cause metallurgical deterioration, it certainly increases slag quantity, acidity and corrosiveness. Whenever possible, such scrap should be used in a balanced condition.

Despite these difficulties, steel scrap will remain in use because it is normally less expensive than pig iron and also available in plentiful supply [13].

Ductile Iron Scrap

Only scrap of ductile iron of known quality should be used.

Ferro Alloys

When Ferro alloys are needed in the charge, the chemical composition of the alloys should be known.

2.3.5.4 Desulphurization

Sulphur helps in the growth of graphite flakes. Thus while producing SG iron the raw materials should have low sulphur content (<0.1%). Sulphur should be removed during melting or by addition of a desulphurising agent like calcium carbide or soda ash.

A variety of compounds are capable of removing sulphur from molten iron. Even manganese desulphurizes but it is an expensive material [13].

More practical desulphurizing agents are [13]:

Caustic Soda	NaOH
Soda Ash	Na_2CO_3
Burnt Lime	$CaCO_3$
Calcium Carbide	CaC_2
Calcium Cyanide	$CaCN_2$

Of these, caustic soda is rarely used because of the health hazard. Lime stone is first reduced to CaO before use. $CaCN_2$ should be ruled out because it increases base iron nitrogen content with the result of a danger of nitrogen gas defects in the castings.

In the tradition of ferrous metallurgy, CaO is the most established of desulphurizing compounds. In ductile iron practice, it is used in basic cupola and electric arc furnace. Limestone ($CaCO_3$) is injected into large ladles resulting in both economical and excellent desulphurization.

2.3.5.5 Spherodizing Treatment Alloys

There are two main alloys in use, nickel magnesium (NiMg) and ferro-silicon-magnesium (FSM). Ferro-silicon-magnesium alloy is commonly used. It should have the composition shown in table 2.2.

Table 2.2 Composition of Ferro-silicon-magnesium Alloy[13].

Mg %	Si %	Ca %	Ce %	Fe %
4-6	45-50	1 max	0.5	balance

2.3.5.6 Melting Techniques for the Production of Ductile Iron

Any furnace which is used for melting of ductile iron must be capable of producing an iron of correct composition at correct temperature. The need to maintain these factors consistently is most important.

Types of Furnaces

Various furnaces are available for the production of ductile iron e.g. fuel fired furnace, electric arc furnace, induction furnace and cupola.

Optimum economy and quality is achieved through cupola-induction furnace duplexing, but this optimum is obtainable for large volume production only. Externally water-cooled cupola furnaces are being used for large scale operations. Water-cooling causes too much heat losses in small cupolas. The main reason for their popularity is the fact that these can operate continuously for several days [13].

Electric Melting

Electric melting is simple, clean and reliable. It also offers the greatest flexibility for melting irons of different grades. Electric arc furnaces are far less popular than induction furnaces. An additional disadvantage of electric arc melting is its noise pollution.

Electric induction furnaces are most common. High frequencies units are usually used for laboratory scale production. In commercial production either 50 or 60 HZ frequencies are being used; the lower the frequency, the better the stirring action and thus, homogenization.

2.3.5.7 Spheroidizing Treatment

One of greatest practical difficulties is the required amount of magnesium into the melt with the necessary degree of consistency. Magnesium boils at 1120°C and when plunged into cast iron at 1400°C, Magnesium metal melts and vaporizes instantaneously, escaping with violence and carrying some of the cast iron with it. Different alloys are used to overcome this difficulty. An alloy of nickel and magnesium (5 or 15% Mg) is efficient as it sinks in molten iron and the reaction is relatively quiet, especially with 5 wt. % alloy. However it is expensive and simultaneously addition of nickel is not always welcomed [23].

Following are four most generally used nickel base magnesium alloys shown in the table 2.3 [13].

Table 2.3: Chemical composition of Ni-base alloy containing magnesium in wt.% [13].

	Mg %	Ni %	Si %	C %	Fe %
Ni-Mg1	15	83	---	2.0	---
Ni-Mg2	15	50	30	---	Bal
Ni-Mg3	4.5	93	---	1.5	---
Ni-Mg4	4.5	60	---	2.5	Bal

A range of magnesium-ferro-silicon alloys are available containing 3 to 15 wt.% magnesium with approximately 45% silicon [23].
Although various methods are employed for introducing magnesium into molten metal, the universally accepted procedure is the sandwich method.

Because of the relatively low density, ferrosilicon- magnesium alloys tend to float on the surface of the liquid iron and react inefficiently. Accordingly, the alloy is placed in the bottom of the treatment ladle, preferably in a pocket‟ moulded in the bottom of the ladle, and covered with steel plate. Before use, the ladle should be heated to a temperature of red heat.

After placing the ferrosilicon-magnesium alloy in the pocket and covering the alloy with the plate, the ladle is positioned so that liquid metal stream does not impinge directly on the magnesium alloy/sandwich. This allows the metal to flow back over the sandwich, which due to presence of cover, delays the reaction of magnesium alloy until a sufficient depth of alloy is built up in the ladle and it also prevents the alloy floating to the surface of the liquid iron.

The ladle should be filled as quickly as possible. This improves the magnesium recovery. The magnesium recovery depends on metal temperature, the quantity of metal treated and the design of the ladle.

2.3.5.8 Amount of Magnesium Required

In practice it is normal to allow for minimum residual magnesium content of 0.035 to 0.04 wt.%, plus the amount of magnesium required to neutralize the sulfur in the iron. The amount of magnesium alloy required depends on two factors:

a) The temperature of metal, the higher the temperature, the lower the recovery of magnesium.

b) Sulphur content of the base iron to be treated; the higher the sulphur content, the greater is the amount of magnesium to be added.

Calculation of Magnesium:

Different formulas are used to calculate the amount of magnesium required. The commonly used formula is [13]:

$$\text{Mg to add (\%)} = \%$$

Fading of Magnesium

There is a gradual decrease in nodularity and an increase in carbide formation, as treated iron is held for some time. The results from different research centers indicated that fading is rather complicated phenomenon.

The simplest component is loss of magnesium content through oxidation or combining with sulphur. Stephen [13] described the following corresponding reactions:

$$Mg + O = MgO$$
$$Mg + S = MgS$$

Considering the relative stabilities of the above two compounds, a more likely reaction is:

$$Mg + S + O = MgO + S$$

If the source of oxygen is an oxide or silica as an oxide, the corresponding reactions are:

$$2Mg + SiO_2 = Si + 2MgO$$
$$2MgS + SiO_2 = Si + 2MgO + 2S$$

It is well established that fading rate is influenced by:

a) Initial Magnesium content; the higher the magnesium content the faster the fading.
b) Temperature; the higher the temperature the faster the fading.
c) Slag handling; the faster the slag is removed, the better for magnesium recovery.
d) Furnace lining; the worst is silica, the best is magnesia.

Magnesium Vs Shrinkage

In Mg treated irons, high Mg content acts to promote carbidic microstructures and increase shrinkage. The magnesium level must be controlled carefully to the cooling rate of the casting to avoid increased chilling tendency. This

cooling rate is described as proportional to the modulus, which is a ratio of casting volume to cooling surface area.

Thus modulus is a more accurate away to describe the cooling of a casting section than just measuring the section size. Of course, all of the carbide stabilizing elements should be kept at relatively low levels to minimize their effect on chill formation. Doing this will allow more of the available carbon to transform into graphite [24].

2.3.5.9 Inoculation

The metallurgical meaning of the word “inoculation” is to provide the melt with seeds or “nuclei” on to which the solid phases grow during freezing. In some cases these nuclei result from adding fines of the same phase which is freezing. If the fines do not completely dissolve before solidification starts, they provide convenient sites for crystal growth. In other cases particles of material other than the one to freeze can perform the same act i.e. heterogeneous nucleation.

The inoculation of ductile irons produces heterogeneous nuclei for the graphite spheroids. Neither their material nature nor mechanism of their action is factually known [13].

The Effects of Inoculations

The principle effects of ductile iron inoculation can be described as follows [25].
The inoculation process:

- Promotes the formation of small and uniformly dispersed graphite in grey iron and increases the nodule count in ductile iron.
- Minimizes the formation of primary iron carbides. These carbides create hard edges on iron castings that make machining difficult, which is a contributing factor to tool breaking.

- Reduces the non-uniform properties within a casting of varying section sizes. Thinner sections solidify at a faster rate than thicker sections. As a result, the properties such as tensile strength of these sections will be different. Inoculation provides more uniform properties within the casting by reducing the solidification rate in thinner sections.
- Improves the tensile strength, impact strength, toughness, wear resistance and machinability of the casting.

Inoculants

Almost every material inoculates to some degree. For effective and well controlled inoculation, ferro-silicon of controlled chemical composition is usually used. Active inoculating elements are: Ca, Al, Ba, Sr, and some others. The chemical composition of commonly used inoculants is given in table 2.4 [13].

Table: 2.4 Chemical Composition of Inoculants [13].

Si %	Ca %	Al %	Ba %	Fe %
75	1.5	1.0	---	Bal
63	2.0	1.0	5	Bal

The inoculants contain relatively little aluminum because aluminum promotes hydrogen pinholes defects, particularly in thin sections [13].

The sizing of the inoculants is usually ½ inches (13 mm) maximum. Since fines do not inoculate effectively, a minimum size limit of 1/6 inches (1.5 mm) is advisable [13].

The inoculant should be stored in closed containers. Its effectiveness deteriorates with time when exposed to open air.

Methods of Inoculation

Cast iron may be inoculated by several methods [25].

- Ladle Inoculation

  Iron is inoculated by adding inoculant to the metal as it is transferred from the furnace to the pouring ladle. The turbulence quickly dissolves the inoculant and evenly disperses it throughout the molten bath.

- In-stream Inoculation

  In many automatic pouring operations, inoculation is done in-the-stream

- In-mould Inoculation

  Inoculants may also be added as a preformed insert placed in the pouring basin of a mould or as granulated inoculant placed in the gating system.

In-stream and in-the-mould inoculation techniques offer little inoculation fade, and generally require less inoculant material to provide the desired results.

2.3.5.10 Solidification of Ductile Iron:

Solidification of SG iron is always associated with properties under cooling. Graphite nuclei grow slowly and then are surrounded by austenite. The combination of austenite and graphite corresponds to the eutectic point at eutectic temperature. Austenite which gets supersaturated with carbon cools and a new equilibrium is established at the graphite/austenite interface. The excess of carbon diffuses towards the graphite nodule where it precipitates out [26-27]

2.3.6 Formation of Carbides in Ductile Iron:

The attainment of mechanical properties in cast ductile iron depends primarily upon the microstructure developed during solidification and solid-state transformation. A recent trend in vehicle component has been towards higher strength and lighter weight to save both materials and energy. Reducing the weight of ductile iron castings by producing thin-wall parts is an important method for saving energy and material. In thin castings the cooling rate is fast

so carbides are formed if special practice and procedure are not adopted. The general reasons for the carbide formation are as under [28].

1. High solidification cooling rate.
2. Carbide-formation elements in the charge.
3. Low CE and / or Si content.
4. Excessive Mg content.
5. Inadequate and poor inoculation (low nodule count).
6. High superheat.

2.3.7 Pouring

Pouring of ductile iron should be done quickly while keeping the pouring basin full through the pour. A majority of ductile iron castings are hand-poured even in highly mechanized foundries. It must be recognized that hand-pouring is a demanding job and the pourer is exposed to some hazard. For this reason and, for potential economic and quality benefits, much effort is being invested in designing pouring machines [13].

2.3.8 Matrix Structure Controls the Properties of Ductile Iron

These irons are cast after treatment of the molten metal with a small quantity of magnesium to change the graphite from a flake to nodular or spheriodal form. Graphite nodules are small and constitute only small planes of weakness in the steel – like matrix, these being about one to hundred the size of those occurring when flake graphite is present. Because of this, and also because the graphite is spheroidal, stress concentrations round the graphite are small, and ductile irons have mechanical properties which relate directly to the strain and ductility of the matrix present as is the case for steels. Unlike gray cast irons, which generally fail with less than about one percentage elongation, ductile iron can deform plastically before fracture and have elongation of 2–25 %. Strengths generally decrease as the elongation increases. When high – strength matrix

structures are obtained by heat treatment, such as normalizing, hardening and tempering, and austempering, it is possible to produce irons with both increased strength and relatively high elongations [14,16].

2.3.9 Properties of Ductile Iron

Mechanical , physical and service properties should be considered for any materials to be used in industrial applications. While mechanical properties takes into account tensile strength, hardness, elongation, proof stress, elastic modulus, impact and fatigue strength, physical properties include damping capacity, conductivity and machinability. The material to be used should be able to survive under the service conditions which can be determined by its wear resistance, heat resistance and corrosion resistance. Below are the properties of SG iron:

- **Tensile strength:**

Ductile iron has higher tensile strength generally ranging from 414 MPa for ferritic grades to 1380 MPa for martensitic or austempered ductile iron grades.

- **Yield strength:**

It is the stress at which the materials begin to have plastic deformation. For ductile irons generally 0.2% offset yield strength is calculated. Yield strength of ductile iron ranges from 275 MPa for ferritic grades to 620 Mpa for martensitic grades.

- **Ductility:**

Ductile irons have considerable ductility. Elongation can sometimes be as high as 25% which is applicable for lower grades only. Austempered ductile irons have the best combination of strength and ductility.

- **Modulus of elasticity:**

Ductile irons show a proportional stress-strain limit which looks similar to that of steels but is hampered by plastic deformation. The modulus of elasticity of ductile varies from 162-170 Gpa.

- **Easy to cast :**

High fluidity enables it to be easily casted.

- **Excellent corrosion resistance:**

Ductile irons have very good corrosion resistance property.

- **Machinability:**

Has a very good machinability due to the graphite which is available in free form. Thus chip formation is easier.

- **Cost per unit strength:**

It is lower than most of the materials. Thus has wide range of applications for which it can be used [27].

2.3.10 Factors Affecting Tensile Properties Of Ductile Iron

2.3.10.1 Chemical Composition

In ferritic ductile irons, the effect of an increase in carbon is to increase the volume of graphite produced, which in turn reduces tensile strength, elongation and hardness. The strength properties of ferritic ductile irons are increased by the addition of elements that go into solid solution in ferrite. Silicon and Nickel are the most important elements to be considered. An increased Silicon content promotes ferrite and strengthens the ferritic matrix. When the Silicon content exceeds 4%, the ferritic matrix becomes sufficiently embrittled to give a lower tensile strength. In pearlitic ductile irons, Silicon promotes ferrite and helps prevent carbide formation. An increase in the Silicon content of pearlitic irons normally results in embrittlement of the pearlitic matrix with accompanying reductions in tensile strength and elongation, although proof strengths continue to increase [15].

2.3.10.2 Temperature

Work at BCIRA has shown that the ductile – to – brittle transition in pearlitic ductile irons is evident in the tensile test by reductions in strength and elongation. The effects of increase in Silicon and Phosphorus on tensile

strength and elongation are in the temperature range between 100 and 300°C. These results illustrate that Silicon and Phosphorus can embrittle pearlitic ductile irons and reduce tensile strength at room temperature, in the same way that they embrittle ferritic ductile irons, where the effect is normally observed in the notched impact test [29].

2.3.10.3 Casting Soundness

Unsoundness in ductile irons can cause dramatic reductions in tensile and other mechanical properties. The factors, which affect the soundness of the castings, are follows:

- The type of mold material used.
- The rigidity of the mold.
- Design of the casting.
- Getting system employed.
- Composition of the iron.
- Thermal history of the metal processing, including Mg treatment temperature and inoculation.

The levels of carbon and silicon, particularly carbon, are important factors governing the soundness of ductile iron castings. The optimum range of carbon is 3.4 to 3.6%. Above or below is dangerous for casting soundness. Above 3.6% carbon, however a larger volume of graphite is precipitated during solidification resulting in higher pressure being exerted on the mold walls. Unless the mold was rigid enough to withstand these pressures then mold – wall movement will occur, increasing the casting volume and promotion unsoundness [15].

2.3.11 Quality Index of Ductile Iron

Quality Index for ductile iron was developed in a statistical study of mechanical properties of a large number of Ductile Iron samples by Siefer and

Orths who identified a relationship between tensile strength and Elongation in the form:

$$\textbf{(Tensile Strength)}^2 \times \textbf{(Elongation)} = Q \qquad (2.8)$$

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 performan. 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. Foundries seeking to optimize the fatigue strength of ductile iron castings need to produce high (Q) value material by taking actions to ensure.

- 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 [18].

2.3.12 Ductile and Brittle Behavior Of Ductile 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 that, 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 appear 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 favour this mode of failure. A simplified explanation for this ductile – to – brittle transition behavior is shown in figure 2.8, 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, 30].

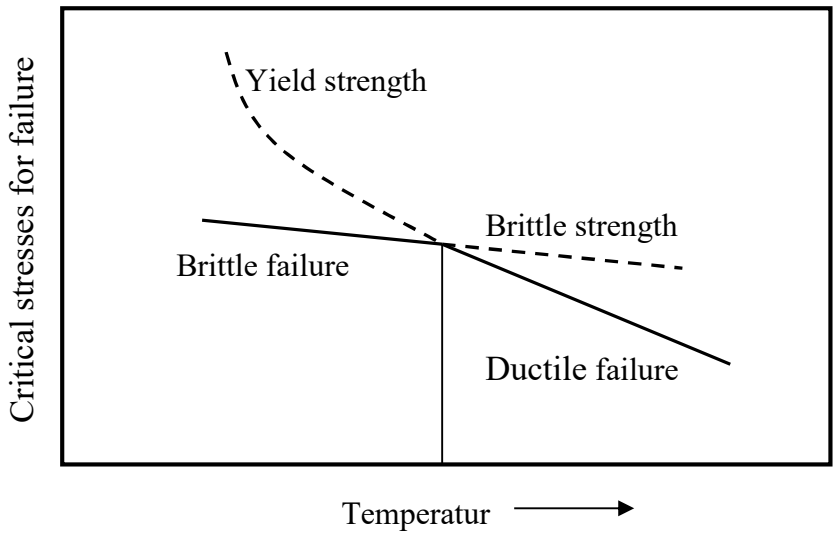


Fig. 2.8: Ductile to Brittle transition occurs as temperature increases [30].

2.2.13 Unique Properties of Ductile 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 cast ability (Foundry men friendly).
- Excellent machinability (As compared to steel).
- Lower density than that of steel.
- Superior surface lubrication properties.
- Better damping characteristics (As compared to the steel).

In addition, on the whole, S.G. iron has a reasonably good reliability [31].

2.3.14 Importance of Ductile Iron

Ductile iron is a very useful invention. It offers the design engineers the option of choosing high ductility, more than 18% elongation, or high strength

exceeding 825 MPa. Ductile iron, when compared to steel and malleable iron castings offers cost savings [32].

Like most commercial cast metals, steel and malleable irons decrease in volume during solidification, and as a result, require attached reservoirs (feeders or risers) of liquid metal to compensate shrinkage. The formation of graphite during solidification causes an internal expansion of ductile iron as it solidifies. As a result, it may be cast free of significant shrinkage defects with feeders that are much smaller than those used in malleable iron and steel. This reduced requirement for feed metal increases productivity of ductile iron and reduces its material and energy requirements resulting in substantial cost savings. The use of most common grades of ductile iron “as-cast” eliminates heat treatment cost, offering a further advantage.

Ductile iron castings are used for many structural applications, particularly those requiring strength and toughness combined with good machinability and low cost. A ductile iron casting can be poured and shipped the same day. As-cast ductile iron castings are consistent in dimensions and weight because there is no distortion or growth due to heat treatment.

Ductile iron is found in increasing applications especially in automobile parts e.g. crankshafts, piston rings and cylinder liners. The use of ductile iron in these applications provides increased strength and permits weight savings.

In agricultural and earth-moving application, brackets, sprockets wheels and track components of improved strength are made of ductile iron.

Ductile iron is also found in general engineering applications including hydraulic cylinders, mandrels, machine frames, switch gears, rolling mill rolls, tunnel segments, bar stock, street furniture and railway rail-clip supports.

2.3.15 Applications Of Ductile Iron

Much of the annual production of ductile iron is in the form of ductile iron pipe, used for water and sewer lines. Ductile iron pipe is stronger and easier to tap, requires less support and provides greater flow area compared with pipe made from other materials. In difficult terrain it can be a better choice than PVC, concrete, polyethylene, or steel pipe. Ductile iron is specifically useful in many automotive components, where strength needs surpass that of aluminum but do not necessarily require steel. Other major industrial applications include off-highway diesel trucks, class 8 trucks, agricultural tractors, and oil well pumps [12]. Since ductile irons have properties similar to steels their application has been extended to

- Engine crank shaft
- Brake caliper, disc – brake anchor, brake anchor plate
- Machine – tool bed
- Electric insulator post and cap
- Steering knuckle
- Rack and pinion of steering assembly
- Piston for impact drills
- Rolling mill rolls
- Moulding boxes and mould box clamps
- Brake shoe for heavy duty brakes
- Glass moulds
- Spacer cage for rolling bearing
- Piston rings
- Wind mill items
- Caskets in Nuclear Industry
- Tractor life arm.
- Check beam for lifting track.

- Mine cage guide brackets.
- Flywheel.
- Thrust bearing.
- Frame for high speed diesel engine.
- Fully machined piston for large marine diesel engine.
- Bevel wheel.
- Hydraulic clutch on diesel engine for heavy vehicle.
- Fittings overhead electric transmission lines.

2.3.16 Heat Treatments

To fully utilize the range of properties beyond the limits of those produced in as-cast condition; Heat treatment is a very valuable tool. The heat Treatments can be carried out on Spheroidal Graphite Iron to achieve the following [33].

1. Increase toughness and ductility,
2. Increase strength and wear resistance,
3. Increase corrosion resistance,
4. Stabilize the microstructure, to minimize growth,
5. Equalize properties in castings with widely varying section sizes,
6. Improve consistency of properties,
7. Improve machinability, and
8. Relieve internal stresses.

2.3.16.1 Annealing

Annealing, sometimes referred to as full annealing, is necessary for castings which are carbidic as – cast. The samples are hold at a temperature of 900 ^{o}C for 2 hours and one additional hour per inch section thickness. Then, cool to 700 ^{o}C and hold there for 5 hrs.

Finally, cool at a maximum rate of 110 ^{o}C per hour to 480 ^{o}C, then air cool. Annealing heat treatment is shown in Figure 2.9.

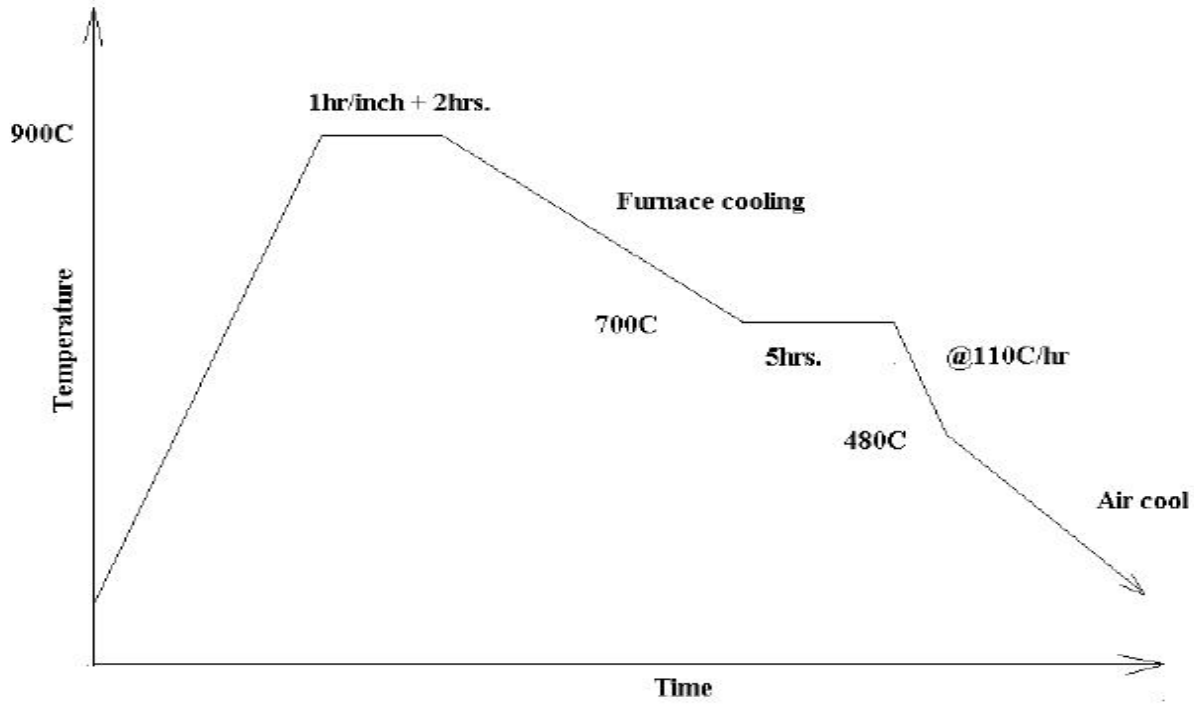


Fig. (2.9): Annealing heat treatment [33].

2.3.16.2 Normalizing

The result of normalizing is a fine pearlite matrix. Heat the casting to 900°C, if massive carbides are present in the structure. Otherwise, heat to A3 + 83 °C. Then, hold for one hour plus one additional hour per inch section thickness. Remove the casting from the furnace and air – cool. Most ductile irons to be normalized are also alloyed with up to 1.5% Cu or up to 0.075% Sn in order to promote a fully pearlitic matrix. The heavier the section the more alloying is needed. To increase hardness and strength Cu is mixed.

When Si content is more than 2.5%, the casting should be fast cooled to get a fully pearlitic matrix. Normalizing heat treatment is shown in Figure 2.10.

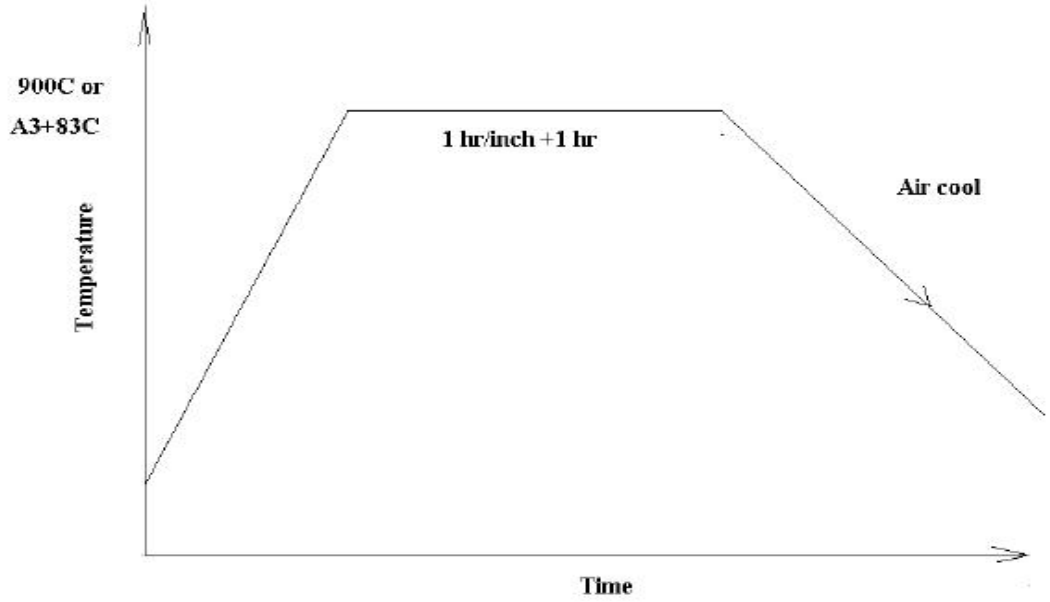


Fig 2.10: Normalizing Treatment [33].

2.3.16.3 Austenitizing

It is the heat treatment process in which the ferrous alloy is held above the upper critical temperature for a sufficiently long time to ensure that the matrix has fully transformed to austenite. Austenitizing is done before any heat treatment process to produce a uniform matrix [33].

2.3.16.4 Tempering

Tempering is a process of heat treating, which is used to increase the toughness of iron-based alloys. It is also a technique used to increase the toughness of glass. For metals, tempering is usually performed after hardening, to reduce some of the excess hardness, and is done by heating the metal to a much lower temperature than was used for hardening. The exact temperature determines the amount of hardness removed, and depends on both the specific composition of the alloy and on the desired properties in the finished product. For instance, very hard tools are often tempered at low temperatures, while springs are tempered to much higher temperatures. More details about this process is described under 2.5

2.3.16.5. The Austempering Process

It is the heat treatment process in which the ferrous alloy is first quenched from temperature higher than upper critical temperature, in a medium allowing a high rate of heat abstraction to prevent high-temperature transformation products, to a temperature where holding leads to 100% bainite formation [34].

Austempered ductile iron is produced by heat-treating cast ductile iron to which small amounts of nickel, molybdenum, or copper have been added to improve hardenability. Specific properties are determined by the careful choice of heat treating parameters.

Austempering involves the nucleation and growth of acicular ferrite within austenite, where carbon is rejected into the austenite. The resulting microstructure of acicular ferrite in carbon-enriched austenite is called ausferrite. Even though austenite in austempered ductile iron is thermodynamically stable, it can undergo strain-induced transformation to martensite when locally stressed. The result is islands of hard martensite that enhance wear properties. Advanced Cast Products uses salt baths for austenitizing, quenching, and austempering in order to achieve close dimensional control. Times and temperatures are tightly controlled throughout the entire process.

Steps in Austempering Process:

1. Heat castings in a molten salt bath to austenitizing temperature.
2. Hold at austenitizing temperature to dissolve carbon in austenite.
3. Quench quickly to avoid pearlite.
4. Hold at austempering temperature in molten salt bath for isothermal transformation to ausferrite [35].

Fig 2.11 shows the austempering procedure [18].

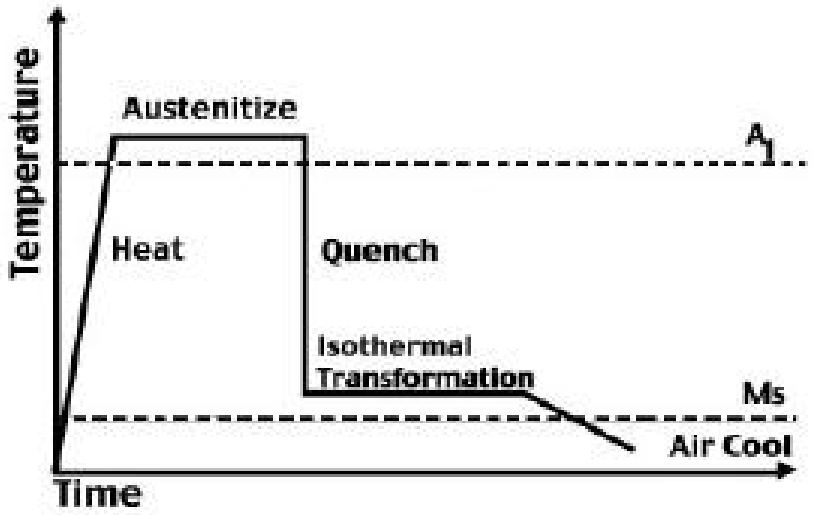


Fig 2.11: Austempering Procedure [18].

- Initial austenitizing times and temperatures (843 to 927°C) are controlled to ensure formation of fine grain austenite and uniform carbon content in the matrix. The precise temperature is grade dependant.
- 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 (232 to 399°C) must stay above the point of martensite formation (except for ASTM A 897 Grade 5).

- In the austempering step which follows austenitizing, the temperature of the final salt bath must also be closely controlled. The austempering step is also precisely timecontrolled, to avoid over- or under-processing. By the end of this step, the desired ADI ausferrite structure has developed.

Fig 2.12 shows the isothermal curve representing austempering process[35].

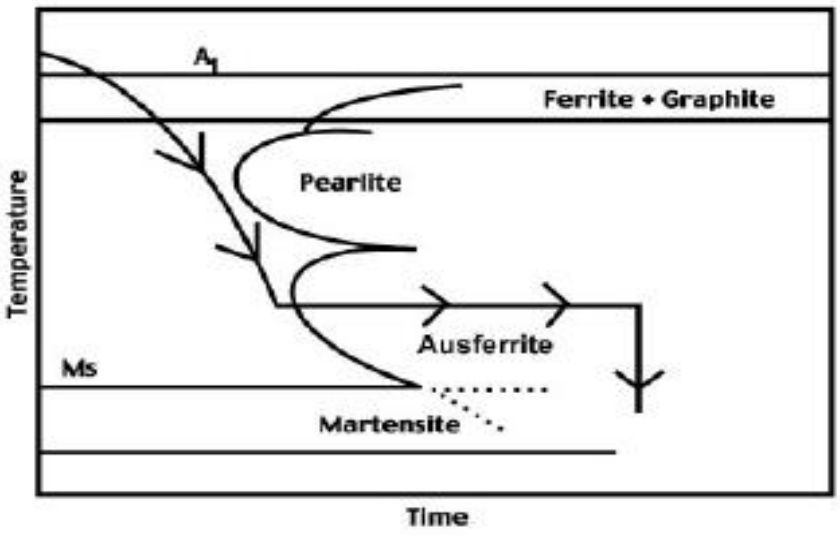


Fig 2.12: Isothermal curve representing austempering process [35].

The figure 2.13: below shows the TTT diagram for the Autempering process. And Figure 2.14: below shows Austempered Ductile Iron microstructure produced by Austenitising at 950ºC and austempered at 350°C for 63min.

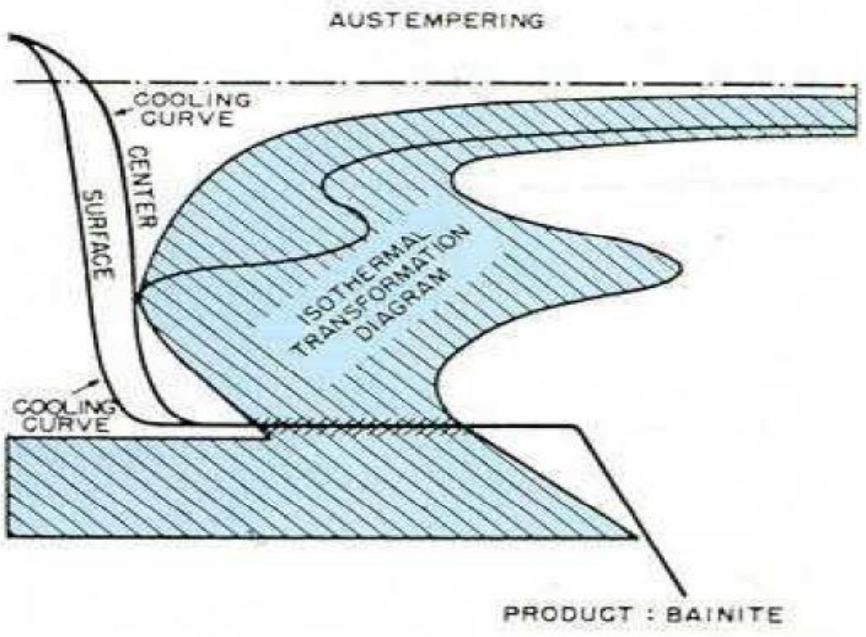


Figure 2.13: Austempering TTT Diagram [35].

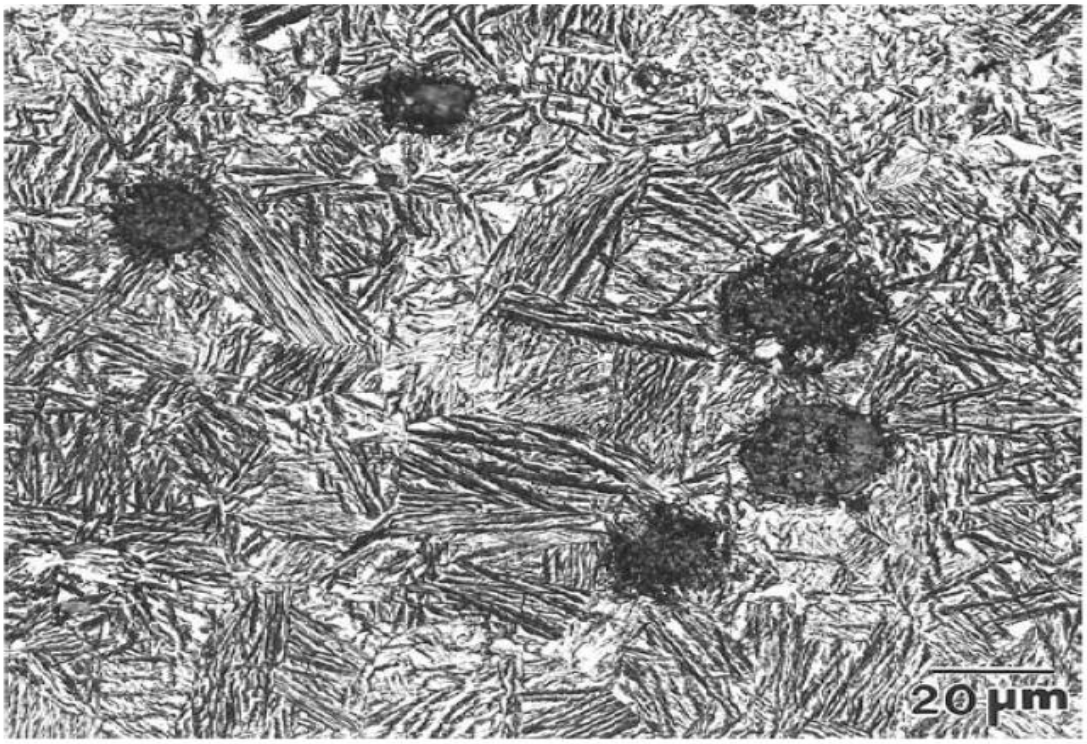


Figure 2.14: Austempered Ductile Iron microstructure [34].

Austempering results in:

1. Enhanced ductility
2. Enhanced toughness
3. Higher Hardness
4. Lesser distortion & Quench cracks than observed after tempering [34].

2.4 AUSTEMPERED DUCTILE IRON (ADI)

To achieve the full potential of ductile iron, austempering heat treatment is adopted. It is possible to achieve much higher ranges of tensile strength and elongation by adopting austempering treatment for ductile iron. For austempering treatment, a defect free casting should be chosen. Any lapse in quality control of starting material will result in inferior end product.

The process is simple. The first stage consists of soaking the castings at austenitizing temperature of 850-950^{o}C. The austenitized castings are then quickly transferred to a liquid bath (salt bath) maintained at temperature range

of 235-425ºC. The transformation is allowed to proceed for a period of up to four hours when austenite transforms to bainite. The castings are finally cooled to room temperature after transformation. By adopting austempering heat treatment process instead of conventional hardening and tempering treatment for ductile iron, the chances of cracking and distortion are reduced. Thus, it becomes possible to carry out rough and final machining before heat treatment.

It is possible to achieve various combinations of high strength, high hardness, limited ductility or lower strength, lower hardness, high ductility by varying the temperature of austempering.

Austempered ductile ir an (ADI) is a ductile iron that has undergone a special, isothermal heat treatment called austempering. 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 [33].

ADI offers superior combination of properties because it can be cast like any other member of the ductile iron family. It offers all production advantages of conventional ductile iron castings. Subsequently, it is subjected to the austempering process to produce mechanical properties that are superior to conventional ductile iron, cast and forged aluminium and many cast and forged steels.

The metal matrix determines the mechanical properties of ductile iron and ADI.

The matrix in conventional ductile iron is controlled by a mixture of pearlite and ferrite. The properties of ADI are due to its unique matrix of acicular ferrite and carbon-stabilized austenite, called ausferrite. Austempering was commercially applied to austempered ductile iron in 1972 A small hallow crankshaft cast by Wagner Casting Company of Decatur, Illinois was machined and installed in a Tecumser products type AE compressor. Meanwhile General Motors successfully implemented ADI rings and pinion gears and constant velocity joints on its production trucks and automobiles [36].

From its infancy in 1972 until today, the application of ADI has grown worldwide. Its annual growth is estimated at 15%. Its combination of high strength- to-weight ratio, wear resistance and low cost have made it a “high-tech” material. Researchers are continuously studying its new parameters [36].

2.4.1 Production of Austempered Ductile Iron

The mechanical properties offered by ADI make it an attractive material for demanding applications. Austempered ductile iron castings must be produced free from surface defects, free from carbides, porosity, inclusions and having a consistent chemical composition.

2.4.1.1 Composition of ADI

In many cases, the composition of an ADI casting differs a little from that of a conventional ductile iron casting. When selecting the composition, consideration should be given to the elements that adversely affect casting quality e.g. formation of carbides and inclusions. A typical composition of ductile iron casting used for making austempered ductile iron is given in the table 2.5 [37].

Table 2.5 Typical Composition of Ductile Iron for Austempered Ductile Iron [37].

C %	Si %	Mn %	Cu %	Ni %	Mo %
3.3-3.7	2.5-2.7	0.25-0.31	0.05-0.8	0.01-0.8	If required 0.25 max

There are three important points to consider when selecting the chemical composition of ADI [38].

- The iron should be sufficiently alloyed to avoid transformation of pearlite but not over alloyed.

- The microstructure should be free from intercellular carbides and phosphides.
- The tendency for chemical segregation should be minimized for the sake of uniformity in the cast component.

2.4.1.2 Effects of Alloying Elements on ADI

Alloying elements are generally used in ductile iron to increase its hardenability. Only the minimum amount of alloys required should be used. Excessive alloying only increases the cost and difficulty producing quality ductile iron necessary for ADI [37].

In many cases, the composition of ADI differs little from that of a conventional Ductile cast Iron. For both conventional Ductile Iron and ADI, during the determination of composition, and hence the raw materials, consideration should be given first to limiting elements which adversely affect casting quality through the production of non-spheroidal graphite, the formation of carbides and inclusions, and the promotion of shrinkage. Another point is the control of carbon, silicon and the major alloying elements that control the mechanical properties and microstructure.

The following are major alloying elements which are used for austempered ductile iron.

Carbon

Increasing carbon in the range of 3 to 4 wt. % increases the tensile strength but has negligible effect on elongation and hardness. Carbon should be controlled within the range of 3.6 to 3.8 wt.%.

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. Increase in the silicon content promotes the impact strength of ADI and lowers the brittle to ductile transition temperature. Silicon should be controlled closely with in the range 2.4-2.8 wt. % [39].

Manganese

Manganese can be both beneficial and harmful as an alloying element. It strongly increases hardenability, but during solidification, it segregates to cell boundaries where it forms carbides and retards austempering reaction.

These microstructural defects and inhomogeneities decrease machinability and reduce mechanical properties. To improve properties and reduce the sensitivity of ADI to section size and nodule count, it is advisable to restrict the manganese level in ADI to less than 0.3% [40].

Copper

It increases hardenability and ductility at austempering temperature below 350 ^{o}C. It may be added up to 0.8 wt.%

Nickel

Nickel may be used to increase hardenability of ADI up to 2.0 wt. %. For isothermal transformation temperatures below 350°C, nickel reduces tensile strength slightly but increases ductility [40].

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 molybdenum content is increased. This deterioration in mechanical properties probably caused by segregation of molybdenum to cell boundaries and the formation of carbides. The level of this element should be restricted by 0.2 wt. % in heavy section castings [41].

2.4.1.3 Austempering heat treatment:

Austempered ductile iron is produced by an isothermal heat treatment known as austempering. It consists of the following steps and it can be represented schematically as shown in Figure 2.15 [38].

- Heating the casting to the austenitizing temperature in the range of 850°C to 950°C.
- Holding the part at austenitizing temperature for a time sufficient to get the entire part to the required temperature and to saturate the austenite with carbon.
- Quenching the part rapidly enough to avoid formation of pearlite to austempering temperature in the range 235°C to 400°C
- Austempering the casting at the desired temperature for a time sufficient to produce matrix of ausferrite.
- Finally cooling the casting to room temperature.

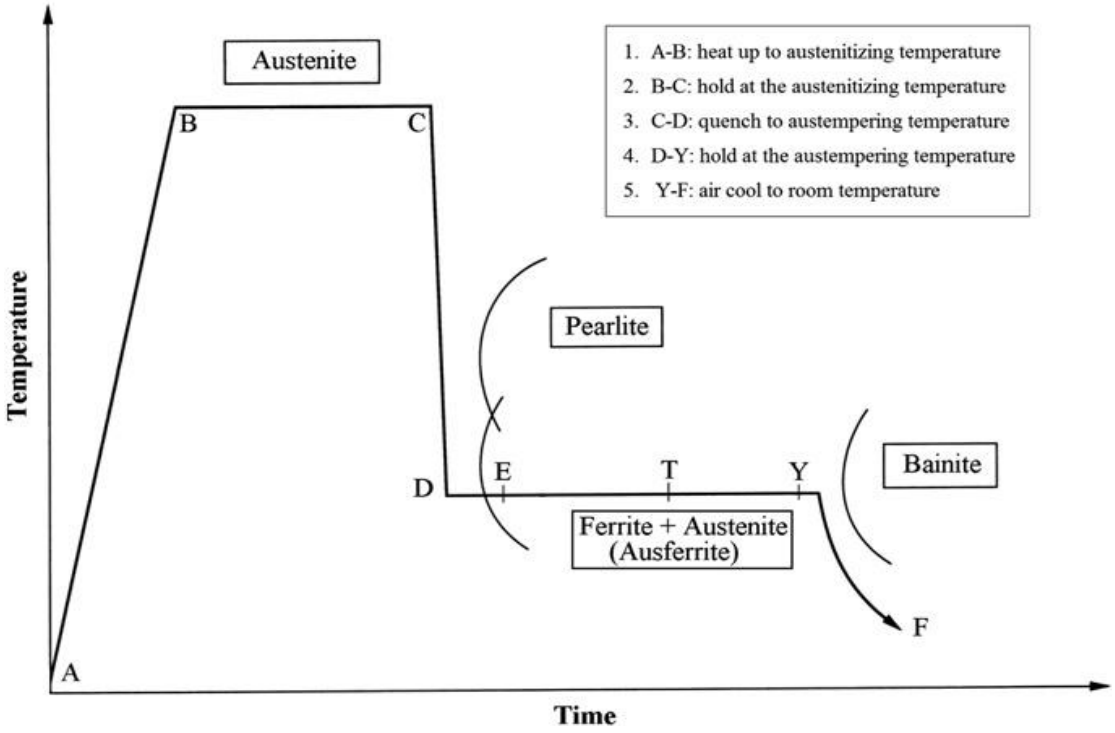


Figure 2.15 Schematic diagram of a typical austempering heat treatment cycle [38].

Austenitizing

The austenitizing temperature controls the carbon content of austenite that affects the structure and properties of austempered castings. High austenitizing temperature increases the carbon content of austenite, which affects the hardenability. It makes the transformation problematic and reduces the mechanical properties after austempering. The higher carbon of austenite requires a longer time to transform. Austenitizing temperature should be minimum required to heat the entire part to the desired austenitizing temperature and to saturate the austenite with equilibrium level of carbon. Austenitizing time is affected by chemical composition, austenitizing temperature, casting section size and type [37].

Austempering

Cooling from austenitizing temperature must be completed rapidly to avoid the formation of pearlite. If pearlite is formed, the strength, elongation and toughness will be reduced.

Austempering temperature is one of the major determinants of mechanical properties of ADI castings. Higher austempering temperature (350 ^{o}C to 400^{o}C produces ADI with lower strength and hardness but high elongation and fracture toughness. Higher austempering temperature produces coarse ausferrite matrix.

For production of ADI with higher strength and greater wear resistance but lower fracture toughness and lower elongation, austempering temperature below 350^{o}C should be employed.

When austempering temperature is selected, the austempering time should be chosen to give a stable structure of ausferrite. Shorter austempering

time will give rise to insufficient diffusion of carbon to austenite to stabilize it and martensite may form when cooling to room temperature. This type of structure would give higher hardness and lower ductility. Excessive austempering time can result in decomposition of ausferrite into ferrite and carbides, so austempering time selection should be appropriate [37].

2.4.1.4 Heat Treatment Considerations

It is important that the heat treatment operation is closely controlled to ensure the production of castings with consistent and satisfactory mechanical properties. A schematic representation of batch austempering heat treatment process is shown in figure 2.16 [41].

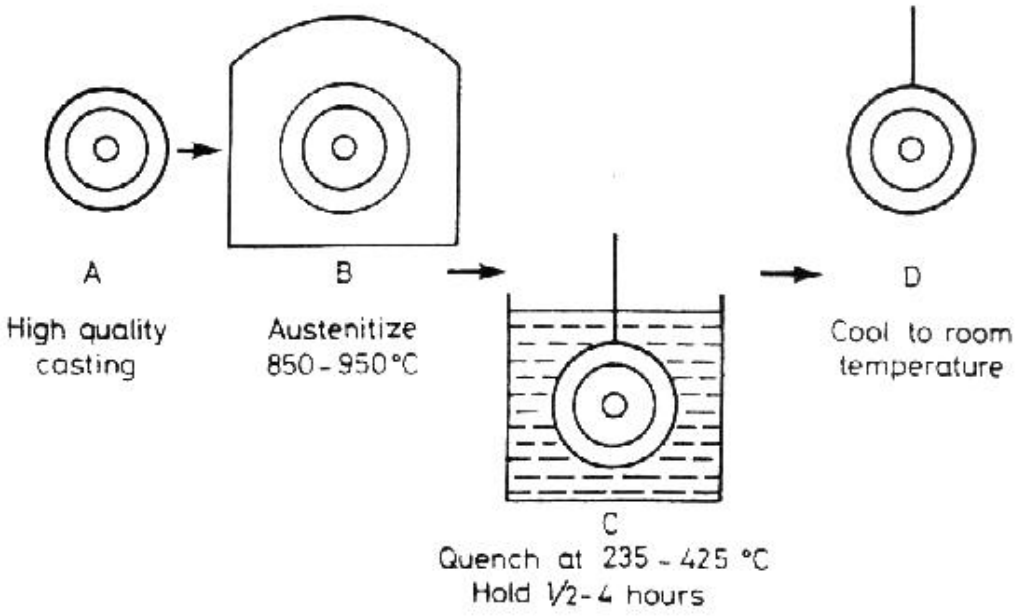


Figure 2.16 Schematic arrangement of the austempering process [38].

2.4.2 Specifications of Austempered Ductile Iron

The ASTM specification A 897 is now most commonly accepted for austempered ductile iron. The five grades specified are detailed in table 2.6 below. They are readily differentiated by their hardness. Tensile, yield and elongation values are also specified as shown in table 2.6 [42].

Table 2.6 Grades and Mechanical propertes of ADI according to [ASTM 897 M-90].

Grade	Min. Tensile		Min. Yield		Elongation	BHN
	Psi.	N/m^2	Psi.	N/mm^2	%	Range
1	125,000	850	80,000	550	10	269-321
2	150,000	1050	100,000	700	7	302-363
3	175,000	1200	125,000	850	4	341-444
4	200,000	1400	155,000	1200	1	388-477
5	230,000	1600	185,000	1300	-	444-555

The British Standards Specification for austempered ductile iron is also used mostly in Europe. The four grades are detailed in table 2.7. They are differentiated by their tensile, proof stress and elongation. The standard EN 1564:1997 is shown in table 2.7 [42].

Table 2.7 Grades and Mechanical propertes of ADI according to [EN 1564:1997].

Material Symbol	Number	Tensile Strength N/mm^2 (Min.)	0.2 % Proof Strength N/mm^2 (Min.)	Elongation %
EN-GJS-800-8	EN-JS 1100	800	500	8
EN-GJS-1000-5	EN-JS 1110	1000	700	5
EN-GJS-1200-2	EN-JS 1120	1200	850	2
EN-GJS-1400-1	EN-JS 1130	1400	1100	1

2.4.3 Cost Benefits of Austempered Ductile Iron:

The price of austempered ductile iron is lower than per kilogram of steel. ADI parts can be produced at a cost less than for steel forging. There are many factors which favour the replacement of steel forging with austempered ductile iron [43].

Excellent castability

It can be cast into complex shapes. Ductile iron has a very high yield strength.

Low Machining Cost

ADI requires less starting material and less metal removal. Prior to austempering, ductile iron exhibits better machinability than the steels. Both ductile iron and ADI produce dense, discontinuous chips that are easily handled.

Heat treatment Savings

Austempering generally costs less than carburizing or induction hardening, and produces a higher degree of uniformity.

Low Energy Cost

Producing a typical austempered ductile iron castings consumes 50% less energy than steel casting and 80% less energy than steel forging for the producing of the similar product.

2.4.4 Properties Of Austempered Ductile Iron

Austempered Ductile iron has the following properties [37, 43]

Strength

It has strength equal to or greater than steel.

Toughness

It has toughness better than ductile iron and equal to or better than cast or forged steel.

Weight

Austempered ductile iron has 10 % less weight than steel due to the presence of graphite nodules.

Fatigue Strength

Austempered ductile iron has equal to or better fatigue strength than forged steel, which increases with machining after heat treatment.

Damping

Austempered ductile iron has five times better damping property than steel. The parts made of this material make less noise.

Properties of ADI Compared to Steel **[48]**

- ADI is much easier to cast than steel
- ADI is approximately 9% lighter than steel
- ADI has minimal draft requirements compared 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

2.4.5 Disadvantages of Austempered Ductile Iron:

There are certain disadvantages of austempered ductile iron. These should be considered before replacing steel parts with ADI. These are as follows [45].

- Welding is not recommended for austempered ductile iron.
- Lower hardness grades can be machined after heat treatment, but higher hardness grades must be machined before heat treatment.

2.4.6 The ADI 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 aluminium alloys.

To optimise 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 behaviour contrasts with that of the metastable austenite retained in steels, which can transform to brittle martensite [46].

A microstructure of ADI and a schematic of the eutectic cell and intercellular boundary region are shown in Figure 2.17. This microstructure is quite different from the case of steels. It consists of blocky unreacted austenite and a two-phase mixture of ferrite and high carbon austenite, named ausferrite.

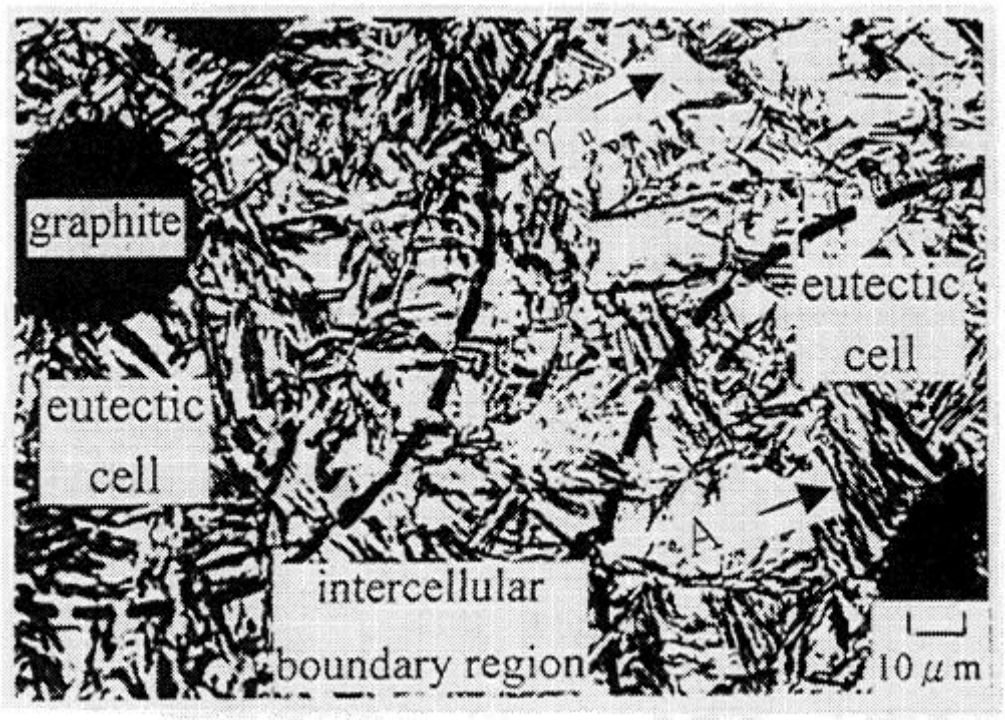


Fig 2.17: Typical microstrure of ADI and schematic of eutectic cell and intercellular boundary region. [A: ausferrite, γ_u: blocky unreacted austenite] [46].

2.4.7 Application of Austempered Ductile Iron:

The development of austempered ductile iron (ADI) has given the design engineers a new group of cast ferrous materials. ADI provides an exceptional combination of mechanical properties equivalent to cast and forged steel.

Dr. Richard Harding [47] overviewed the wide range of application of austempered ductile iron.

ADI is now established in many major markets:

Gears

One of the earliest applications of ADI was for the manufacture of gears. Pioneers in this field were:

- General Motors, USA for rear axle hypoid pinion and ring gears for cars.

- Chinese foundries, who used similar gears for light and medium trucks [46].
- Kymi Kymmence, Finland, for various applications including general engineering gear boxes, rolling mill drives, and large segmented ring gears for cement mills, rotary kilns and forestry machines [49, 50].

Crankshafts

One of large potential markets of austempered ductile iron is crankshafts for high-powered diesel engines [47]. Crankshafts for air-conditioning and refrigerator application have been produced by companies such as Wagner Casting Co. USA and Sulzer Brothers, Switzerland [51]

Transmissions

There are following examples for the transmissions [47].

- A large number of tripot housings have been used by General Motors, USA, in front- wheel drive units.
- Differential spiders manufactured by Kymi Kymmene, Finland.

Suspensions

The austempered ductile iron suspensions have been used in the industry. The example includes war shoe restraints made by Advance Cast Products, USA, for use in suspension units of lorry tractor units [47].

Railway Engineering

A variety of austempered ductile iron components have been used in European and American railway applications e.g. Axle boxes produced by SKF, Sweden, for railway vehicles and pick up arms for railway track maintenance machines, produced by Sulzer Brothers, Switzerland [42, 51].

Bracket Trailer

The Australian trucking industry had interesting challenges in terms of hauling freight over rough and isolated distances that can be exceptionally long. Different experiments were carried out with different materials. They failed the on-road test. Ultimately a ductile iron casting was designed and austempered to ASTM Grade 2 ADI. The bracket was 900 mm long and 1200 mm high, with a weight of 105 kg. These ADI brackets successfully traveled over 322,000 km without any problem [52].

Agricultural Applications

Due to its high strength-to-weight ratio as well as its increased wear resistance, austempered ductile iron is well suited for agricultural applications from suspension to ground-engaging components [53].

Defence

The defence industry has been relatively slow to adopt ADI, however some of the applications include track links, armor and various hardware for trucks and armored vehicles [37].

Construction Equipment
Heavy Truck/Trailers
Light Vehicles and Buses
Mining/Forestry Equipment
Farm and Oilfield Machinery
Conveyor Equipment and Tooling
Energy Generation
Sporting Goods

ADI is also finding new markets. In particular the burgeoning Renewable Energy field has identified ADI components to replace conventional materials solutions. Meanwhile specialist applications of the other Austempered cast

irons (AGI, and CADI) are growing and there are niche markets for the unique Carbo- Austempering process. [54]

2.5 TEMPERING HEAT TREATMENT

Tempering is an ancient heat-treating technique. The oldest known example of tempered martensite is a pick axe which was found in Galilee, dating from around 1200 to 1100 BC [2]. The process was used throughout the ancient world, from Asia to Europe and Africa. Many different methods and cooling baths for quenching have been attempted during ancient times, from quenching in urine, blood, or metals like mercury or lead, but the process of tempering has remained relatively unchanged over the ages. Tempering was often confused with quenching and, oftentimes, the term was used to describe both techniques. In 1889, Sir William Chandler Roberts-Austen wrote, "There is still so much confusion between the words "temper," "tempering," and "hardening," in the writings of even eminent authorities, that it is well to keep these old definitions carefully in mind [54].

It is the heat treatment process in which the quench-hardened or normalized ferrous alloy is reheated to a temperature below the transformation temperature and cooling is done at any desired rate. Tempering is done to relieve thermal residual stresses and for improving ductility & toughness. The enhancement in ductility by tempering leads to depreciation in the hardness & strength [34].

The reduction in hardness is usually accompanied by an increase in ductility, thereby decreasing the brittleness of the metal. Tempering is usually performed after quenching, which is rapid cooling of the metal to put it in its hardest state. Tempering is accomplished by controlled heating of the quenched work-piece to a temperature below its "lower critical temperature". This is also called the lower transformation temperature or lower arrest (A1) temperature; the temperature at which the crystalline phases of the alloy, called ferrite and

cementite, begin combining to form a single-phase solid solution referred to as austenite. Heating above this temperature is avoided, so as not to destroy the very-hard, quenched microstructure, called martensite.

Precise control of time and temperature during the tempering process is critical to achieve the desired balance of physical properties. Low tempering temperatures may only relieve some of the internal stresses, decreasing brittleness while maintaining a majority of the hardness. Higher tempering temperatures tend to produce a greater reduction in the hardness, sacrificing some yield strength and tensile strength for an increase in elasticity and plasticity [55].

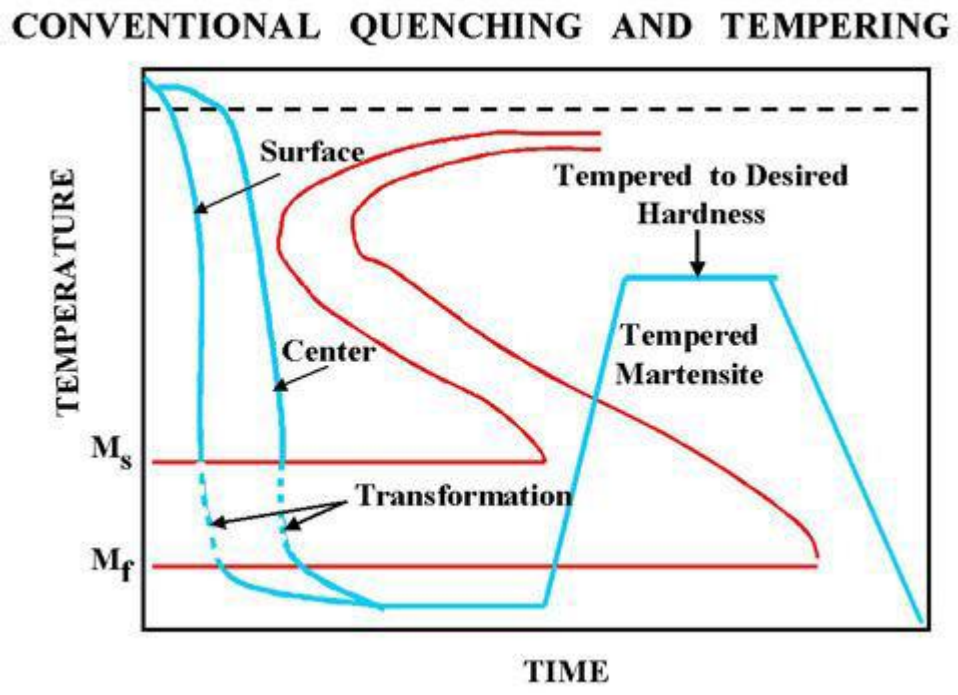


Figure 2.18: Conventional Quench & Tempering Process.
(http://info.lu.farmingdale.edu/depts/met/met205/tempering.html)

Tempering results in:

1. Reduced brittleness
2. Enhanced ductility & Toughness
3. Reduced Hardness & Strength

From the available literature, it is quite evident that attempts were made to understand and predict the behaviors of Austempered Ductile Iron (ADI) that includes the study of Effect of Tempering Treatment on the Microstructure and Hardness, the response of matrix structure to heat treatment, structure and properties correlation and its mechanical properties and possible application. A brief review of some literatures in this area is presented under here.

In 1999, Wen Italic have investigated the effect of tempering conditions on the mechanical properties of austempered ductile iron [56]. A modified austempering treatment was carried out to obtain a microstructure mixture of ausferrite and tempered martensite by stopping the austempering reaction before step 1 was completed, and resuming tempering at 200°C for 7.2 ks then cooled to room temperature. The change in the microstructure and the related changes in mechanical properties of ADI after tempering were investigated. The results show that tempering at 200°C after austempering, decreased the sensitivity of mechanical properties to austempering conditions. Independent of austempering temperature, tempering at 200°C also led to significant improvement in mechanical properties with increasing martensite content. Strength and toughness could be improved to exceed the maximum values obtained without tempering, and these strengthening effects were particularly obvious at martensite content below 5%. With tempering at 200°C, the required austempering time for obtaining the maximum values of mechanical properties could be shortened from 10.8 ks without tempering to 1.8 ks with tempering, and the effective austempering time interval was also extended.

The previous study indicated that tempering at 200°C could increase the ductility and toughness of ADI having a mixed structure of ausferrite and martensite austempered at 400°C. The same result was also observed by Rounds Italic in the study of ADI austempered at 371°C followed by tempering at 371°C. The results mentioned above show that the ductility and toughness of upper ADI having a mixed structure of ausferrite and suitable amount of

tempered martensite might be of the same level as those of ausferrite structure alone.

Sushil K. Putatunda et al. investigation [57] was to create the austenite free austempered ductile cast iron or completely ferrite matrix ductile iron. In this work the tempering is done after austempering treatment and the physical and mechanical properties were compared with austempered ductile cast iron. The chemical composition of the ductile iron was C 3.45%, Cu 0.3%, Si 2.48%, Ni 1.5% and the rest was other elements. Two batches of samples were prepared; one batch of samples was processed by conventional austempering treatment. The second batch was tempered at 484°C for 2hrs after austempering treatment, and finally these samples were air cooled to room temperature. After these treatments, different properties and characterizations such as tensile test, metallography and X-ray diffraction, hardness and fractography were conducted and analyzed.

At the lower austempering temperature (260°C) the microstructure was needle shaped ferrite with bright etching austenite in which graphite nodules were dispersed. On the other hand at a higher temperature (385°C) coarse and feathery ferrite characteristic of upper banitie was observed. The samples which were additionally tempered at 484°C after austempering, show totally ferritic microstructure. The X-ray diffraction profile of non-tempered samples shows both ferrite and austenite peaks, while the additional tempered samples show only ferrite planes between 42° to 46°, and between 72° to 92°. This indicates that after tempering only ferrrite present in these samples and austenite was below the resolution of X-ray. The hardness of non-tempered samples decreases as the temperature was increased. On the other hand, the hardness of the tempered samples at 260°C and 315°C had much lower value than that of non-tempered samples, whereas at 385°C had higher than that of the non-tempered samples. The yield strength of non-tempered samples decreases as the temperature increases from 260 to 385°C. When the yield strength of tempered samples was compared with non-tempered samples there

was no significant difference, but when ductility of these samples was compared, they found that there was significant decrease in ductility for the temperature 316°C and 385°C.

For the austempered samples at 260°C there was no decrease in ductility. The fracture surface of non-tempered samples shows a mixed mode of fracture with cleavage and few dimples. The fracture surface of tempered samples (austempered at 385°C) shows a cleavage type of fracture, while there was not much difference in the appearance of the fracture surface at 260°C tempered and non-tempered samples.

Haseeb et al. [58] have compared the tribological behavior of quenched, tempered and austempered ductile iron at the same hardness level (445KHN) The chemical composition of ductile iron was 3.6% C, 2.5% Si, 0.6% Mn, 0.01% S and 0.02% P and balance Fe. For the heat treatment, all the samples were austenized at 860°C then quenching was done in brine and tempered at 350°C. For austempering austentized samples, the samples were transferred quickly to a lead bath maintained at 350°C and kept in that bath for 2 min, after which they were allowed to cool in still air for attaining the same hardness level. They found that wear rate increases with the increase of sliding distance. The rate of increase is higher during the initial (running-in) period. After a sliding distance of $2*10^3$ m the wear rate attains a steady state value. The wear rate of austempered ductile iron is always lower than that of the quenched and tempered ductile iron. The rate of increase of wear rate as a function of load is much higher in the case of quenched and tempered samples than in austempered samples.

Comparison of two samples shows that the wear resistance of austempered iron is better than that of quenched and tempered iron at longer sliding distances. The morphology of the wear scars on quenched and tempered, and austempered ductile iron shows that in both cases scars show a similar morphology. These sliding marks running more or less parallel to each

other are seen on the micrographs. The dark patches are thought to represent oxidized surface. The quenched and tempered samples show a decreased hardness below the worn surface while an increase in hardness is observed in the case of austempered samples. The difference between the wear resistance of quenched and tempered, and austempered ductile irons both having the same initial hardness can be related to the difference in their microstructures.

Metallography and XRD reveal that the microstructure of quenched and tempered iron consists mainly of tempered martensite. XRD has revealed that austempered ductile iron used in the present study contains 23% retained austenite. However, the XRD pattern of the worn surface recorded after the wear test does not show any retained austenite peaks, indicating that during the wear process, retained austenite has been transformed and this transformation was martenstic transformation.

Rashidi et al. have investigated the effect of tempering conditions on the mechanical properties of ductile iron with dual matrix structure [59]. Tempering is the most important heat treatment process that was applied to quenched steel and cast iron. The objectives of this process include reducing the brittleness of the material, improvement of toughness and ductility, and reducing the probability of cracking. The composition of the material analyzed was (in Wt %) 3.56% C, 1.94% Si, 1.33% Ni, 0.28 % Mn, 0.29% Mo, 0.017% P, 0.012% S. In order to obtain a complete ferrite structure, the samples were first heat treated at 950°C for 2 hrs, and then the samples were tempered at 300 °C, 400°C, 450°C, 500°C, 600°C for 1 hr, and also at 500°C for 30, 90,120, 150, and 180 min. Finally, the samples were machined down to standard dimension and then tension experiment was carried out.

It was seen that by increasing the tempering temperature, there was a rise in elongation percentage, prior to the sudden jump that occurred within the range of 400–500°C, followed by a slow gradual increase. Therefore, if the aim is to achieve high toughness and ductility, the dual phase ductile iron with

ferrite-martensite matrix structure should be tempered at temperature higher than 500°C. Again as the tempering temperature increased, the yield strength ultimate tensile strength initially decreased then within the range of 400–500 °C remained roughly constant and then there was a rise in elongation percentage for tempering up to 120 min before it is finally dropped. The reason for this reduction was likely to be due to a phenomenon called temper embitterment. Within the temperature range of 400–500°C, both strength and yield stress decrease .

Longer duration of tempering period at 500°C increases the elongation percentage, for tempering period up to 120 minutes reduces strength and yield stress, thereafter, they both go up again. For any combination of temperature of tempering and tempering period and of up to 120 minutes. the amount of ultimate tensile strength can satisfactorily be obtained from the mastercurve's strength-tempering parameter.

CHAPTER 3
EXPERIMENTAL WORK

CHAPTER 3
EXPERIMENTAL WORK

This chapter introduces the experimental procedures used to examine the effect of tempering conditions on the hardness properties and microstructures of Austempered Ductile Iron Alloyed with 1.6% copper and 1.6% nickel.

3.1 RAW MATERIALS

The raw materials were produced at the international center for cast metals technology of the BCIRA in Alvechurch, Birmingham, UK. The iron was produced from a 200 Kg charge of low Mn good quality steel scrap, high purity graphite, foundry-grade ferrosilicon, copper and nickel and melted in medium frequency induction furnace. The melt was super heated to 1520^{o}C so as to ensure homogenisation and tapped into a ladle at 1450 ^{o}C on to 1.8% Mg ferrosilicon alloy containing cerium. After inoculation using 0.67% foundry grade FeSi containing nominally 75% silicon, the melt was cast at 1400 ^{o}C into keel blocks.

All the as cast keel had a fully ferritic structure with a nodule count between 50 and 75 nodules per mm^2 and a degree nodularity in excess of 90%.

The alloy was purchased and the chemical composition, as shown in Table 3.1, was determined spectrographically. From these raw materials austempered ductiles iron alloys were produced according to the heat treatment cycles shown in Table 3.2 [11].

Table 3.1**:**Composition of the materials determined spectrographically.

Element	wt%
C	3.30
Si	2.60
Mn	0.35
S	0.008
P	0.01
Mg	0.04
Ni	1.60
Cu	1.60

Table 3.2**:** Heat treatment conditions of an alloyed nodular cast iron [11]**.**

Matrix Structure Type	Austenitising Temperature (°C)	Austenitising Time (mins.)	Austempering Temperature (°C)	Austempering Time (mins.)
Initially ferritic	1000	30	**360**	**180**
Initially ferritic	1000	60	**360**	**180**
Initially ferritic	1000	120	**360**	**180**
Initially ferritic	1000	180	**360**	**180**
Initially ferritic	1000	360	**360**	**180**

3.2 SAMPLES PREPARATION:

For different conditions the solid blocks of Austempered Ductile Iron were cut using power hacksaw, and then, the samples were machined ground and polished, and to the required dimensions suitable for various experiments. The equipements used to prepare samples are shown Figures 3.1- 3.4..



Figure (3.1) : Cutting machine.



Figure (3.2) : Mounting machine.



Figure (3.3) : Grinding machine.



Figure (3.4) : Polishing machine.

3.3 TEMPERING HEAT TREATMENT

To select the tempering temperatures and times to be used in this work a literature review was conducted.

Austempered ductile iron samples were subjected to the tempering heat treatment using the furnace CARBOLITE-RHF 1500 shown in Figure 3.5. The heat treatment conditions are shown in Table 3.3.



Figure (3.5) : Furnace used in the study**.**

Table 3.3 : Heat Treatment Conditions.

Tempering Temperature (ºC)	**Tempering Time (mins)**
300	120
400	120
450	90
	120
	150
500	120
550	120
600	120
660	120

3.4 HARDNESS MEASUREMENT:

The heat treated samples with dimensions of 10×10×10 mm (Figure 3.6) were polished by emery papers (or SiC papers) of different grades prior hardness measurement. Rockwell Hardness test was performed at room temperature to measure the macro hardness of the ADI specimens in C scale (Figure 3.7). The load 150 kg was applied through the square shaped diamond indentor for few seconds during testing of all treated and untreated samples. A minimum of four measurements for each sample were taken covering the whole surface of the specimen and then the average is taken to obtain the final hardness result.

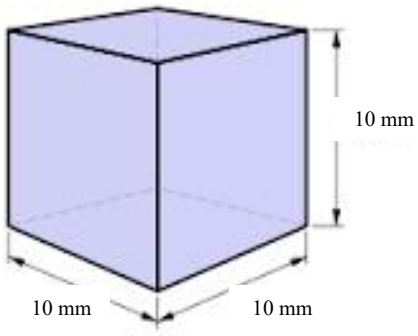


Figure (3.6) : The samples dimensions.



Figure (3.7) : Hardness test machine used in this work.

3.5 METALLOGRAPHIC EXAMINATION:

All samples were subjected to metallographic examination before and after each heat treatment condition. Conventional metallographic preparation techniques were used.

In order to determine the microstructure, the specimens were cut to the desired size, and then ground with a group of emery papers changing from #320 to #500 to #800 to # 1000. After the grinding process the polishing process was carried out by using of the rotary disk with the Al_2O_3 addition Figures (3.1-3.4). The etching operation was done with the %2 nital (2% conc. Nitric acid in methanol solution), and finally the microstructures were taken by using the optical micoscopy (Figure 3.8). on each heat treatment condition.



Figure (3.8) : Optical microscope.

CHAPTER 4
Results

CHAPTER 4
Results

4.1 INTRODUCTION

A brief resume of the experimental results obtained is now given. It is important to note that all hardness values given here are an average of at least 5 readings but in most cases, a larger number of tests.

Prior to tempering all specimens were austenitized at 1000^{o}C for different times and austempered at 360^{o}C for 3 hours. the effect of these conditions on the mechanical properties were invistigated by M. Alaalam [4-10]. In figures (4.1 – 4.5) the zero tempering temperature was included i.e. Austenitizing at1000^{o}C for 30 minutes without tempering. This was done solely fore comperison with tempered specimens.

4.2 THE EFFECT OF TEMPERING TEMPERATURE

The results of the effect of tempering temperature on the hardness values are summorized in tables (4.1 - 4.5), and illustrated in figures (4.1 - 4.5).

The optimum hardness values were obtained at a tempering temperature of 450^{o}C Figures (4.1 - 4.5), and then dropped down slightly as the tempering temperature reached 550^{o}C. After that, the values decreased rapidly with further increase in tempering temperature at 660^{o}C. Generally the same trend was obtained in all the samples austenitized for different times (15, 30, 60, 120, 180 and 360 minutes) before tempering as shown in figures (4.1 - 4.5).

Table (4.1): Effect of tempering temperature on the hardness values of ADI austenitized for 30 mins.

Austenitizing condition	Austempering conditions	Tempering condition	Hardness values HRC
1000°C / 30 mins	360°C / 180 mins	Without tempering	28
1000°C / 30 mins	360°C / 180 mins	300°C / 120 mins	26.5
1000°C / 30 mins	360°C / 180 mins	400°C / 120 mins	29
1000°C / 30 mins	360°C / 180 mins	450°C / 120 mins	32.5
1000°C / 30 mins	360°C / 180 mins	500°C / 120 mins	30
1000°C / 30 mins	360°C / 180 mins	550°C / 120 mins	27
1000°C / 30 mins	360°C / 180 mins	600°C / 120 mins	22.5
1000°C / 30 mins	360°C / 180 mins	660°C / 120 mins	11

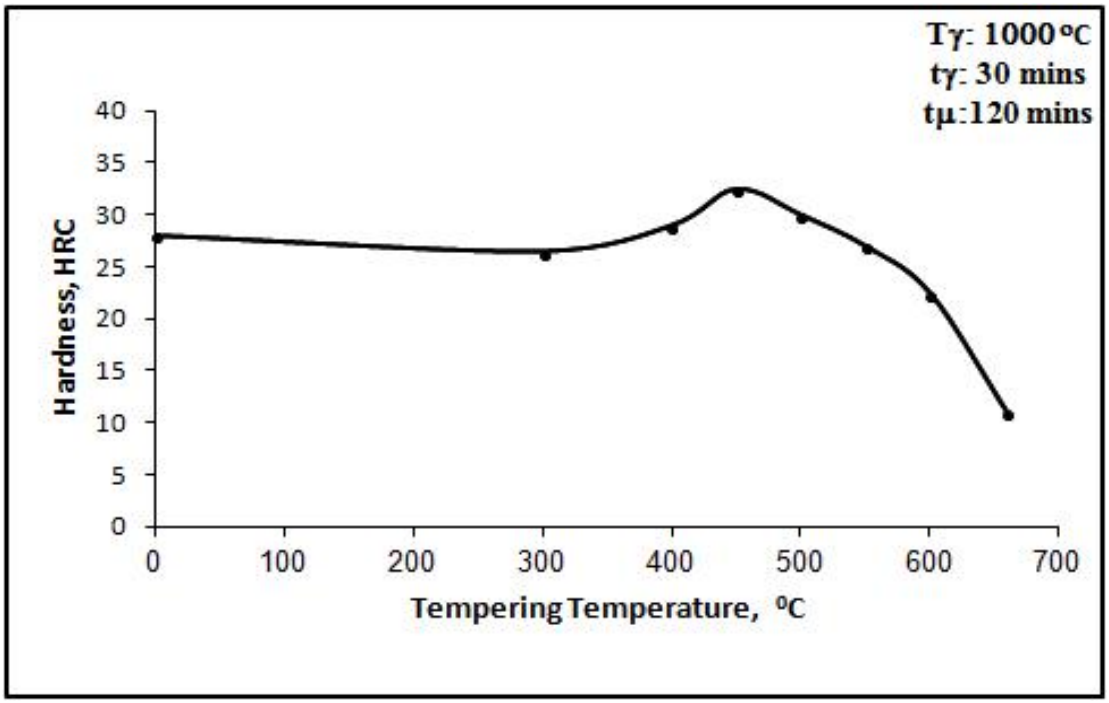


Figure (4.1) : Effect of Tempering Temperature on the hardness values of ADI austenitized for 30 mins.

Table (4.2): Effect of tempering temperature on the hardness values of ADI austenitized for 60 mins.

Austenitizing condition	Austempering condition	Tempering condition	Hardness values HRC
1000°C / 60 mins	360°C / 180 mins	Without tempering	32.5
1000°C / 60 mins	360°C / 180 mins	300°C / 120 mins	34.5
1000°C / 60 mins	360°C / 180 mins	400°C / 120 mins	33.5
1000°C / 60 mins	360°C / 180 mins	450°C / 120 mins	34
1000°C / 60 mins	360°C / 180 mins	500°C / 120 mins	34.5
1000°C / 60 mins	360°C / 180 mins	550°C / 120 mins	31
1000°C / 60 mins	360°C / 180 mins	600°C / 120 mins	23
1000°C / 60 mins	360°C / 180 mins	660°C / 120 mins	9.5

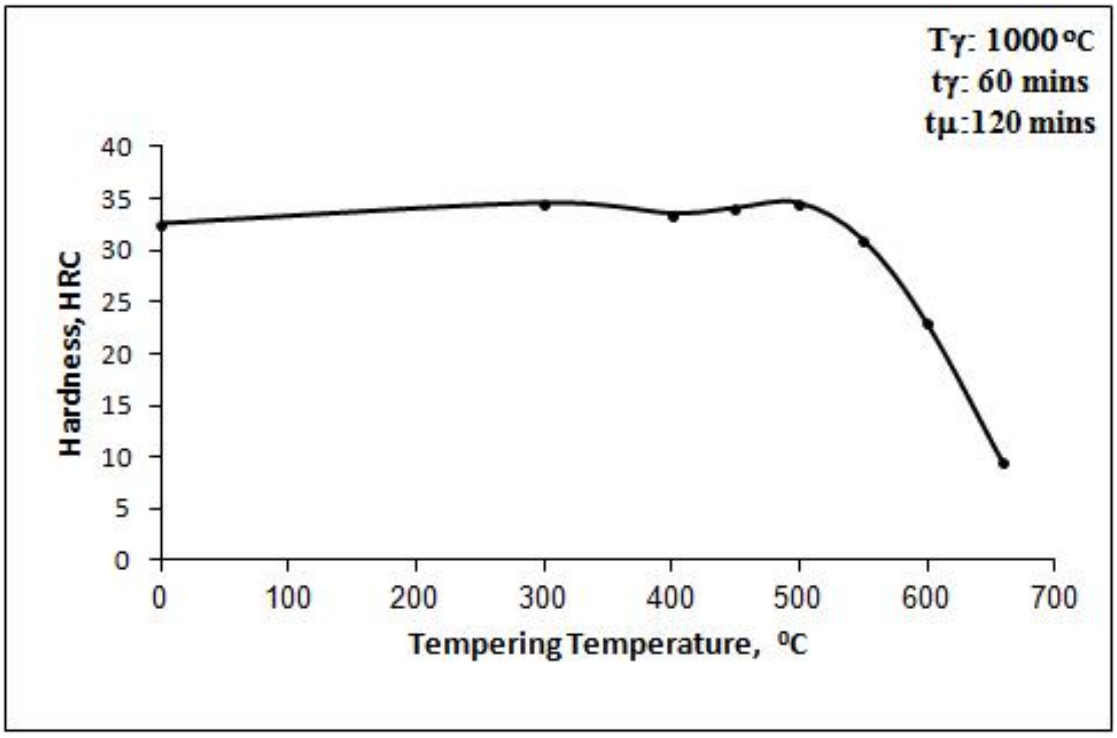


Figure (4.2) : Effect of Tempering Temperature on the hardness values of ADI austenitized for 60 mins.

Table (4.3): Effect of tempering temperature on the hardness values of ADI austenitized for 120 mins.

Austenitizing condition	Austempering condition	Tempering condition	Hardness values HRC
1000°C / 120 mins	360°C / 180 mins	Without tempering	31
1000°C / 120 mins	360°C / 180 mins	300°C / 120 mins	35
1000°C / 120 mins	360°C / 180 mins	400°C / 120 mins	33
1000°C / 120 mins	360°C / 180 mins	450°C / 120 mins	35
1000°C / 120 mins	360°C / 180 mins	500°C / 120 mins	31
1000°C / 120 mins	360°C / 180 mins	550°C / 120 mins	29.5
1000°C / 120 mins	360°C / 180 mins	600°C / 120 mins	24
1000°C / 120 mins	360°C / 180 mins	660°C / 120 mins	14

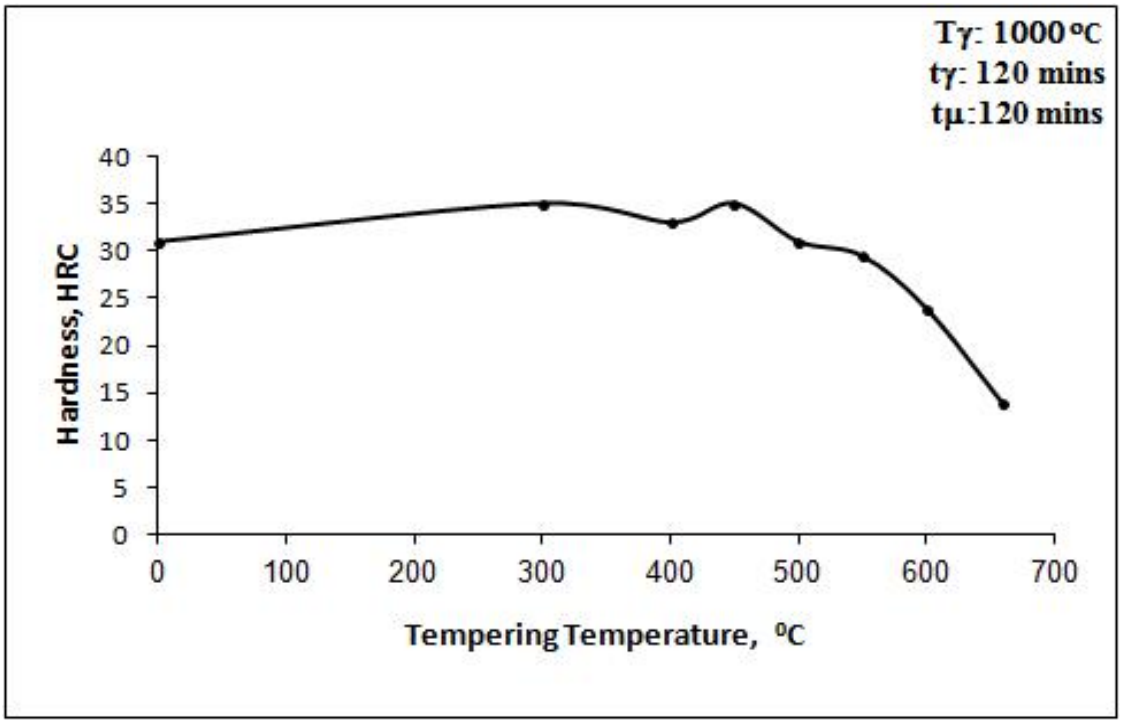


Figure (4.3) : Effect of Tempering Temperature on the hardness values of ADI austenitized for 120 mins.

Table (4.4): Effect of tempering temperature on the hardness values of ADI austenitized for 180 mins.

Austenitizing condition	Austempering condition	Tempering condition	Hardness values HRC
1000ºC / 180 min	360ºC / 180 mins	Without tempering	29
1000ºC / 180 min	360ºC / 180 mins	300ºC / 120 mins	32
1000ºC / 180 min	360ºC / 180 mins	400ºC / 120 mins	34
1000ºC / 180 min	360ºC / 180 mins	450ºC / 120 mins	32.5
1000ºC / 180 min	360ºC / 180 mins	500ºC / 120 mins	30.5
1000ºC / 180 min	360ºC / 180 mins	550ºC / 120 mins	27.5
1000ºC / 180 min	360ºC / 180 mins	600ºC / 120 mins	22.5
1000ºC / 180 min	360ºC / 180 mins	660ºC / 120 mins	10

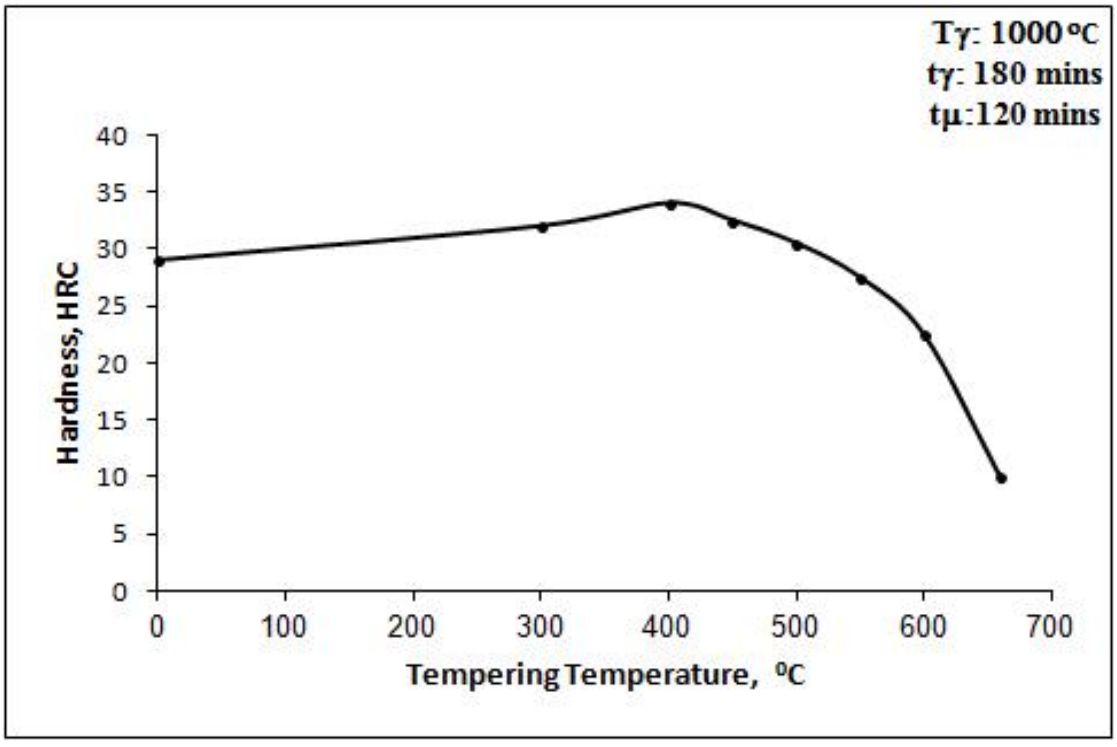


Figure (4.4) : Effect of Tempering Temperature on the hardness values of ADI austenitized for 180 mins.

Table (4.5): Effect of tempering temperature on the hardness values of ADI austenitized for 360 mins.

Austenitizing condition	Austempering condition	Tempering condition	Hardness values HRC
1000°C / 360 min	360°C / 180 mins	Without tempering	25
1000°C / 360 min	360°C / 180 mins	300°C / 120 mins	30
1000°C / 360 min	360°C / 180 mins	400°C / 120 mins	30
1000°C / 360 min	360°C / 180 mins	450°C / 120 mins	33
1000°C / 360 min	360°C / 180 mins	500°C / 120 mins	31
1000°C / 360 min	360°C / 180 mins	550°C / 120 mins	26
1000°C / 360 min	360°C / 180 mins	600°C / 120 mins	21
1000°C / 360 min	360°C / 180 mins	660°C / 120 mins	9.5

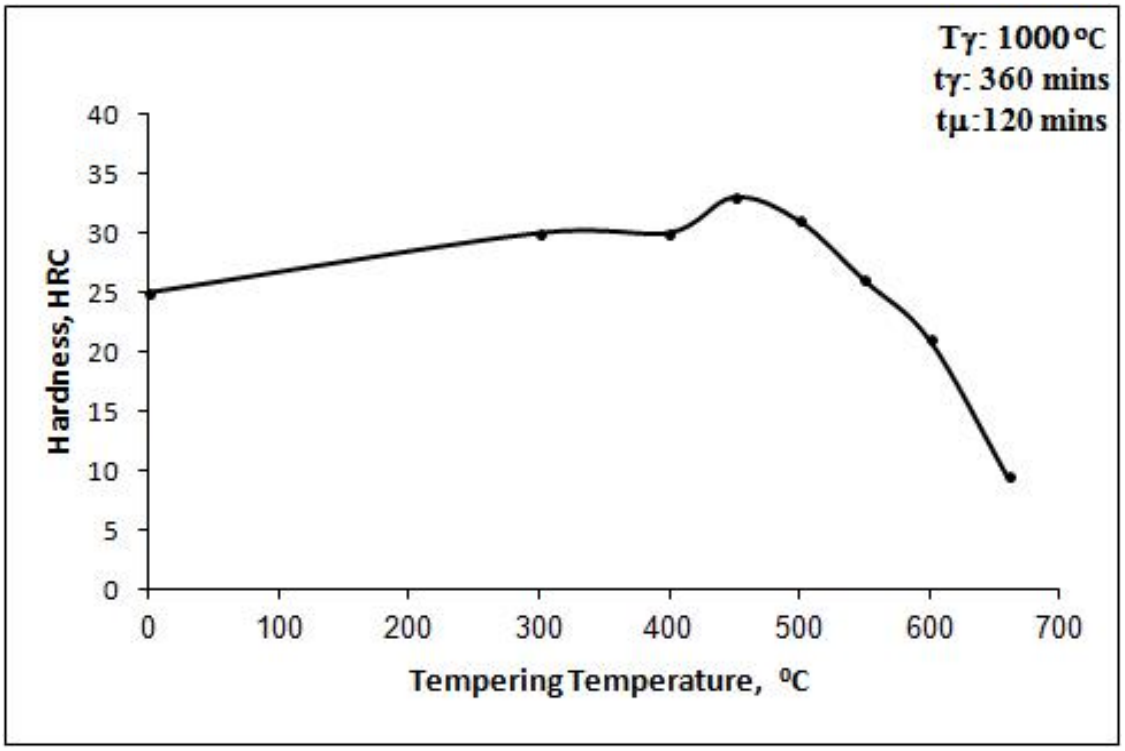


Figure (4.5) : Effect of Tempering Temperature on the hardness values of ADI austenitized for 360 mins.

4.3 THE EFFECT OF TEMPERING TIME

The effect of tempering times at 450ºC for 90, 120 and 150 mins. are summorized in tables (4.6, 4.7 and 4.8). The samples were heated before tempering as follows :

The austenitizing conditions

austenitizing temperature = 1000 ºC.

austenitizing times = 120,180 and 360 mins.

Austempering conditions

austempering temperature = 360 ºC.

austempering time was 180 mins.

As shown in figures (4.6-4.8), the hardness values decreased as the tempering time was extended from 90 to 150 min. Although, the hardness values decresae slightly as the tempering time increases as shown in figures (4.6, 4.7 and 4.8). The samples follow the same trend even if the samples austenitized for different austenitizing times (120, 180 and 360) mins. Also, The most important result in that all samples of the tempering treatment are higher than samples before tempering.

Table (4.6): Effect of tempering time on the hardness property of specimens tempered at 450ºC after austenitizing condition at 1000ºC/120 mins and austempering condition at 360ºC/180 mins.

Austenitizing condition	Austempering condition	Tempering condition		Hardness values HRC
		Temperature ºC	Time mins	
1000ºC /120 mins	360ºC / 180 mins	450	90.	36
1000ºC /120 mins	360ºC / 180 mins	450	120	35
1000ºC /120 mins	360ºC / 180 mins	450	150	35

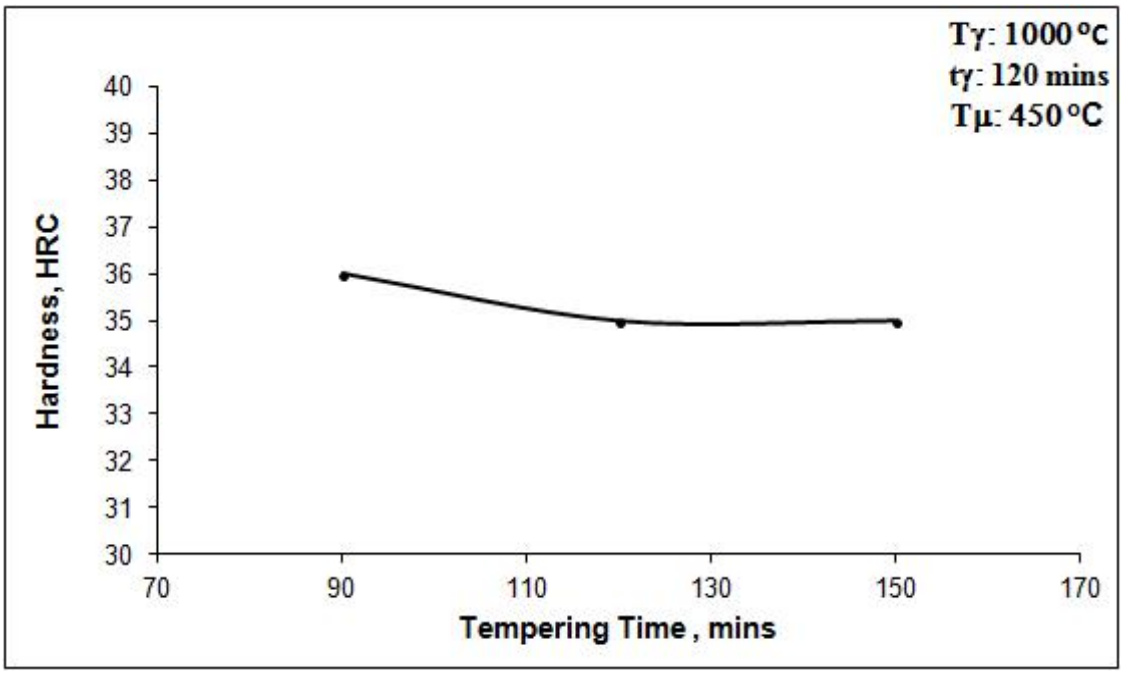


Fig. (4-6) : Effect of Tempering time on the hardness of ADI tempered at 450°C and austenitizing time 120 mins.

Table (4.7): Effect of tempering time on the hardness property of specimens tempered at 450°C after austenitizing condition 1000°C/180 mins. and austempering condition 360°C/180 mins.

Austenitizing condition	Austempering condition	Tempering condition		Hardness values HRC
		Temperature °C	Time mins	
1000°C /180 mins	360°C / 180 mins	450	90.	33.5
1000°C /180 mins	360°C / 180 mins	450	120	32.5
1000°C /180 mins	360°C / 180 mins	450	150	32

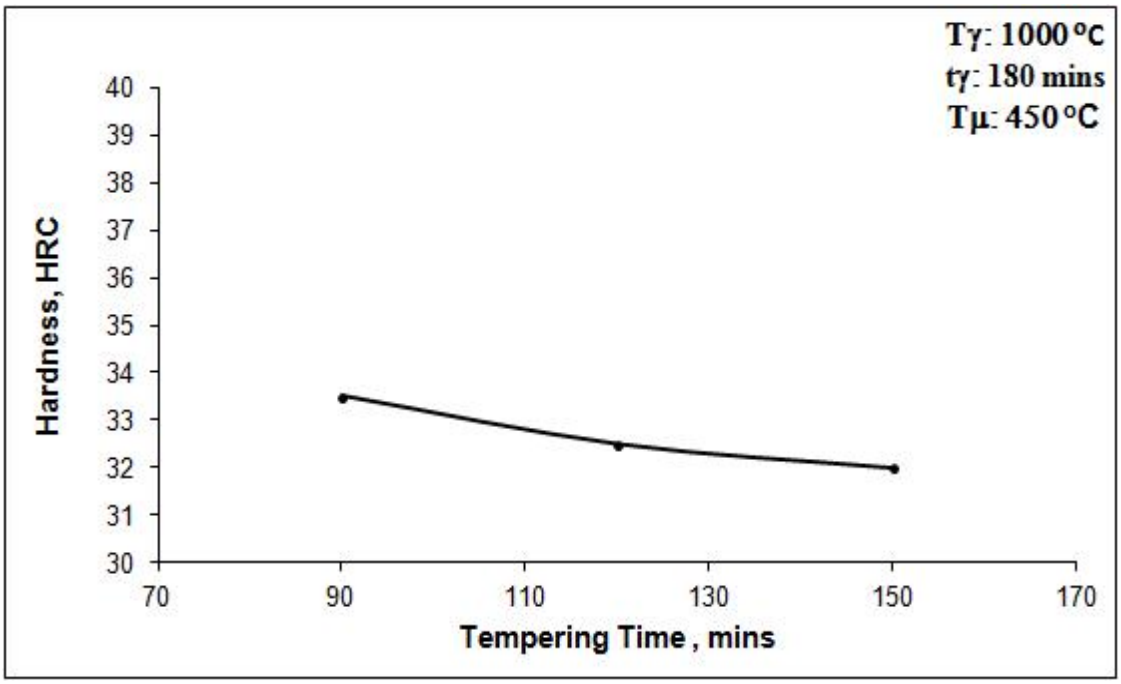


Fig. (4-7): Effect of Tempering time on the hardness of ADI tempered at 450 ^{0}C and austenitizing time 180 mins.

Table (4.8): Effect of tempering time on the hardness property of specimens tempered at 450°C after austenitizing condition 1000°C/360 mins. and austempering condition 360°C/180 mins.

Austenitizing condition	Austempering condition	Tempering condition		Hardness values HRC
		Temperature °C	Time mins	
1000°C /360 mins	360°C / 180 mins	450	90.	34
1000°C /360 mins	360°C / 180 mins	450	120 .	33
1000°C /360 mins	360°C / 180 mins	450	150	31.5

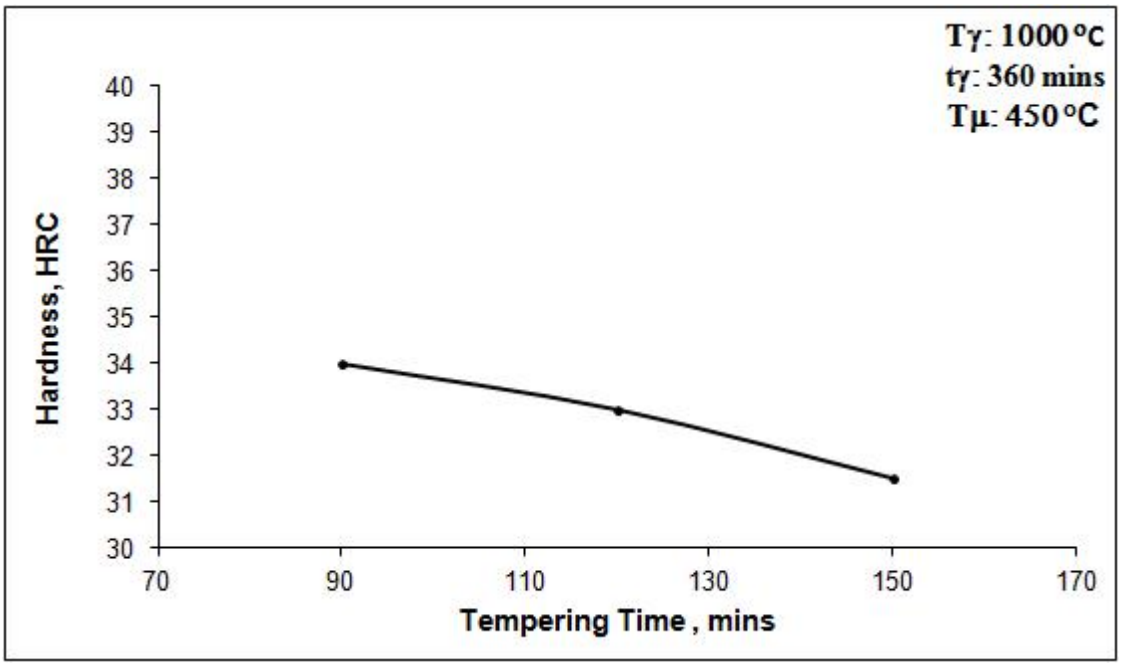


Fig. (4-8): Effect of Tempering time on the hardness of ADI tempered at 450^0C and austenitizing time 360 mins.

CHAPTER 5
DISCUSSION

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DISCUSSION

5.1 INTRODUCTION

It is well established that the austempered ductile iron (ADI) is becoming a vital industrial material. The mechanical properties of ADI could be enhanced to become attractive for some applications. Since, very little work has been conducted about the effect of tempering treatment on the mechanical properties of ADI alloys, therefore, the aim of this research is to investigate the effect of tempering of some austempered ADI specimens on the hardness values. In this chapter, the results of the evoluation of hardness and microstructural characteristics are discussed.

Different phases appear in the micrrostructure of ADI. This microstructure is a mixed structure of ausferrite and suitable amount of temperated martensite and graphite. The effect of tempering on austemped samples is discussed in relation to microhardness and hardness properties.

Different variables have been studied in the current research to investigate their effects on the hardness values of ADI. These variables as following :

1. Austenitizing time at constant austenitizing temperature T_γ (1000^{o}C) and tempering time tμ (120 mins)

2. Tempering temperature at constant tempering time.

3. Tempering time at constant tempering temperature.

All samples were austempered at 360^{o}C for 180 mins before tempering.

In the first section of the discussion the effect of tempering temperature (Tμ) on hardness values and microstructure is disscused where possible comparison is also made with values of mechanical properties reported in other studies[56, 57 and 59]. The reltionship between austenitizing time (t_γ) and tempering time (tμ) is also made.

In another section, the effects of tempering temperature (Tμ) by varying the temperature between 300ºC and 660ºC and holding for 120 mins are discussed in relation to hardness properties and microstructure.

5.2 EFFECT OF TEMPERING TEMPERATURE ON THE HARDNESS VALUES AND MICROSTRUCTURE OF ADI TEMPERED FOR 120 MINS

In general, tempering has the following effects :

1 Tempering or softening of any martensitic formed during austempering .

2 Reduses the acicularity of the bainitic needles.

Both (1) and (2) increase the ductility at the expense of some reduction of tensile strength.

In this study, the hardness value is ncreased gradually in the temperature range of 300 to 500ºC with the appearance of highest values of hardenss in the range between 450ºC -500ºC. Then, there is a decline in hardness with a high rate beyond 500ºC. The value of hardness at 660ºC is very low compared to the one measured at low tempering temperature as shown in figures (5.1).

The influence of tempering temperature on hardness of tempered austempered ductile cast iron is reported in Tables (4.1-4.5) and figure (5.1a and b) It is evident, that there is a gradual increase in hardness values of the samples as the tempering temperature is increased from 300 ºC to 450 ºC in this range there was an increase in hardness due to the formation of martensite at the expense of the unreacted austenite. heating the specimens in the furnace was the reason behind this change. Moreover, the nodules ferrite decreased in size and increased in numbers.

In the range between 400 and 550ºC, the hardness reached the highest values and that because the increase in transformation rate of unreacted austenite to martensite and probaly due to some precipition of carbon.

After 500ºC, hardness started to decline charply and that because the increase in amount and size of austenite at the expense of martensite and ferrite. Moreover, the carbon decomposed and secondary graphite formed.

In fact, the effect of tempering temperature of samples austenitized for different times (between 30 and 360 minutes) followed the same trend.

Also, at higher tempering temperatures the bainite needles are less acicular, figures (5.2-5.5). This may explain the decresae in hardness with tempering temperature. The samples tempered at 660ºC show totally ferritic microstructure.

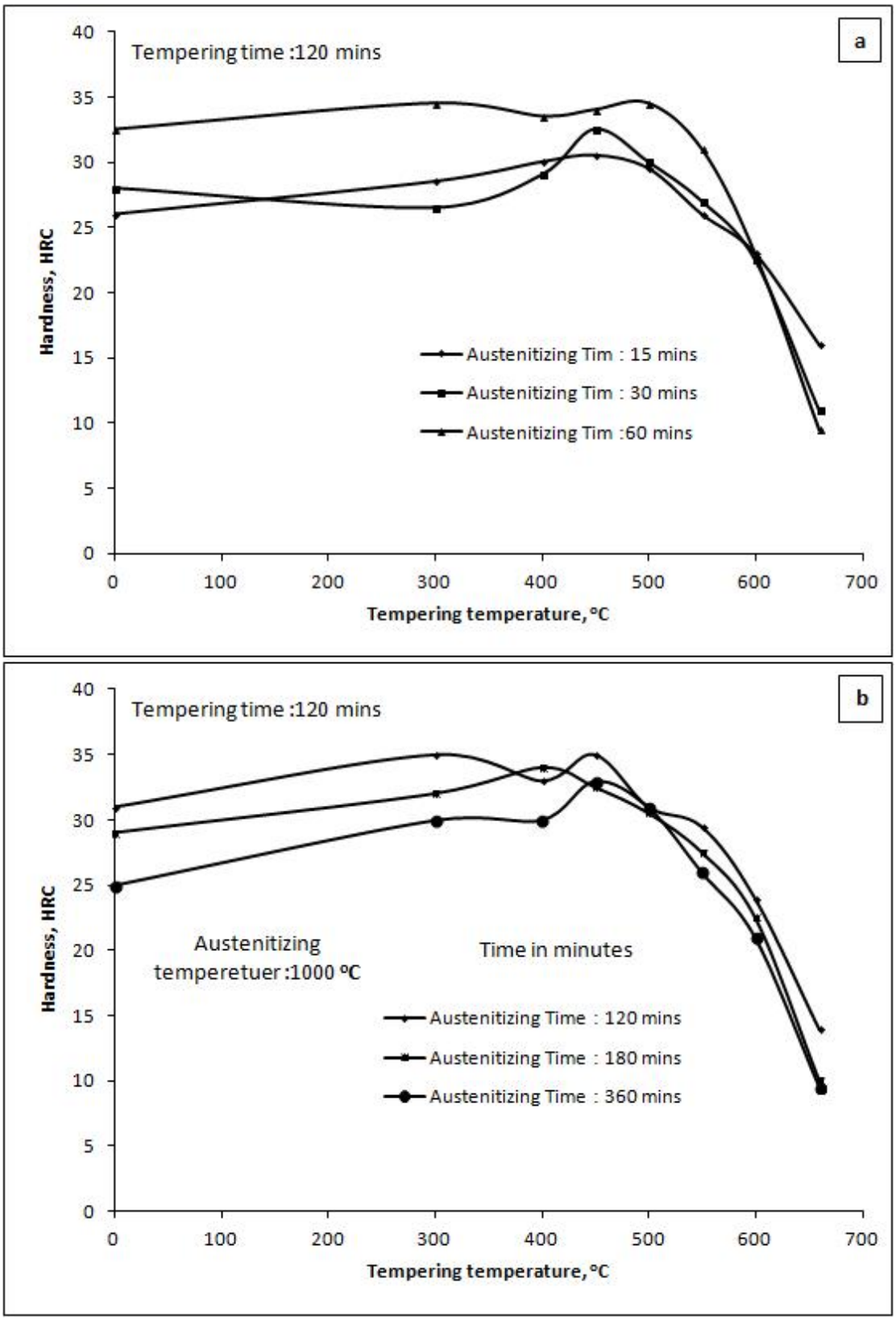


Fig. (5.1) Effect of tempering temperature on the hardness of ADI, (a) : short austenitizing time , (b) : long austenitizing time.

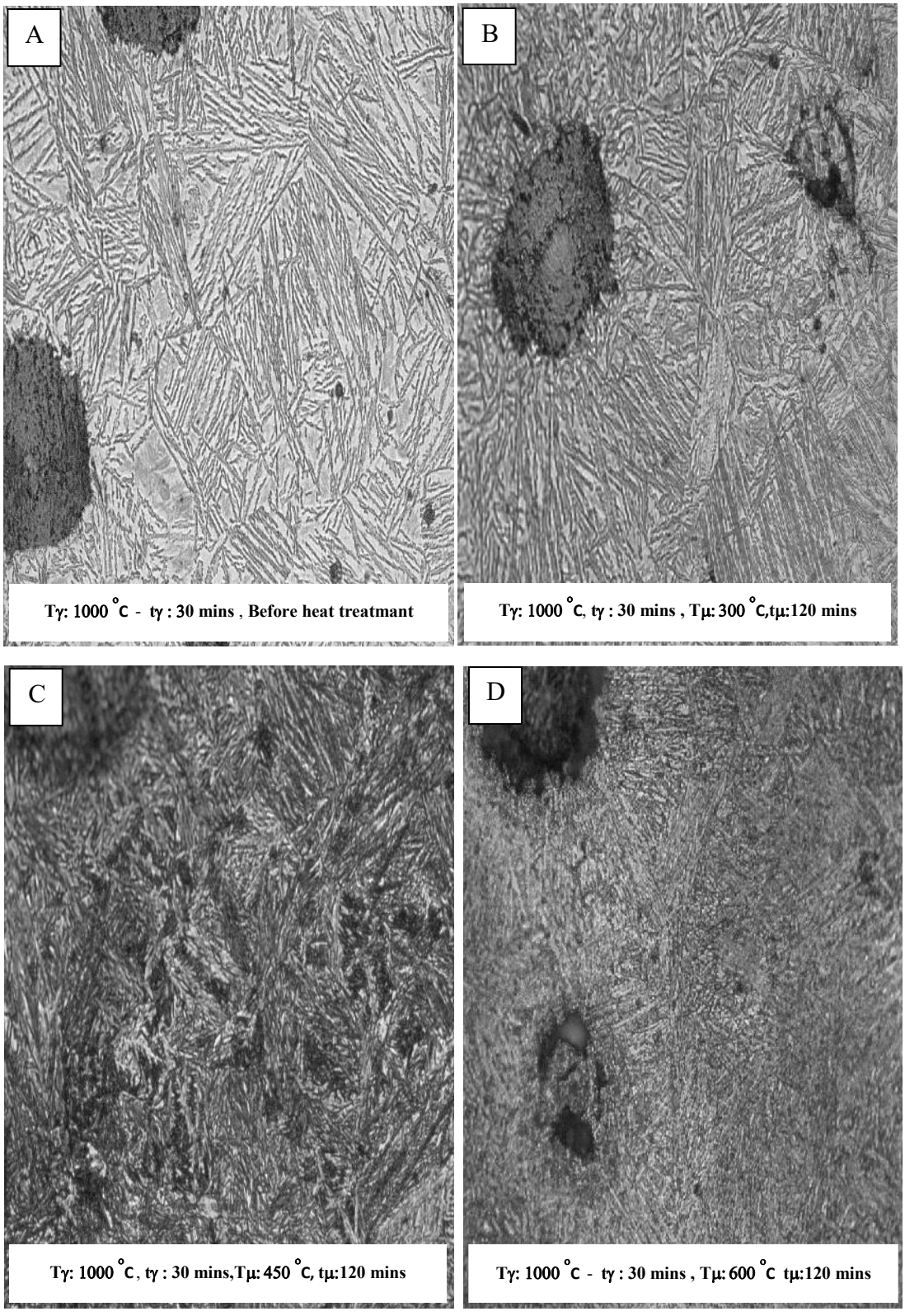


Fig. (5.2) Microstructures of samples before and after tempering at 300, 450 and 660°C for 120 mins. and austenitized for 30 mins (500x).

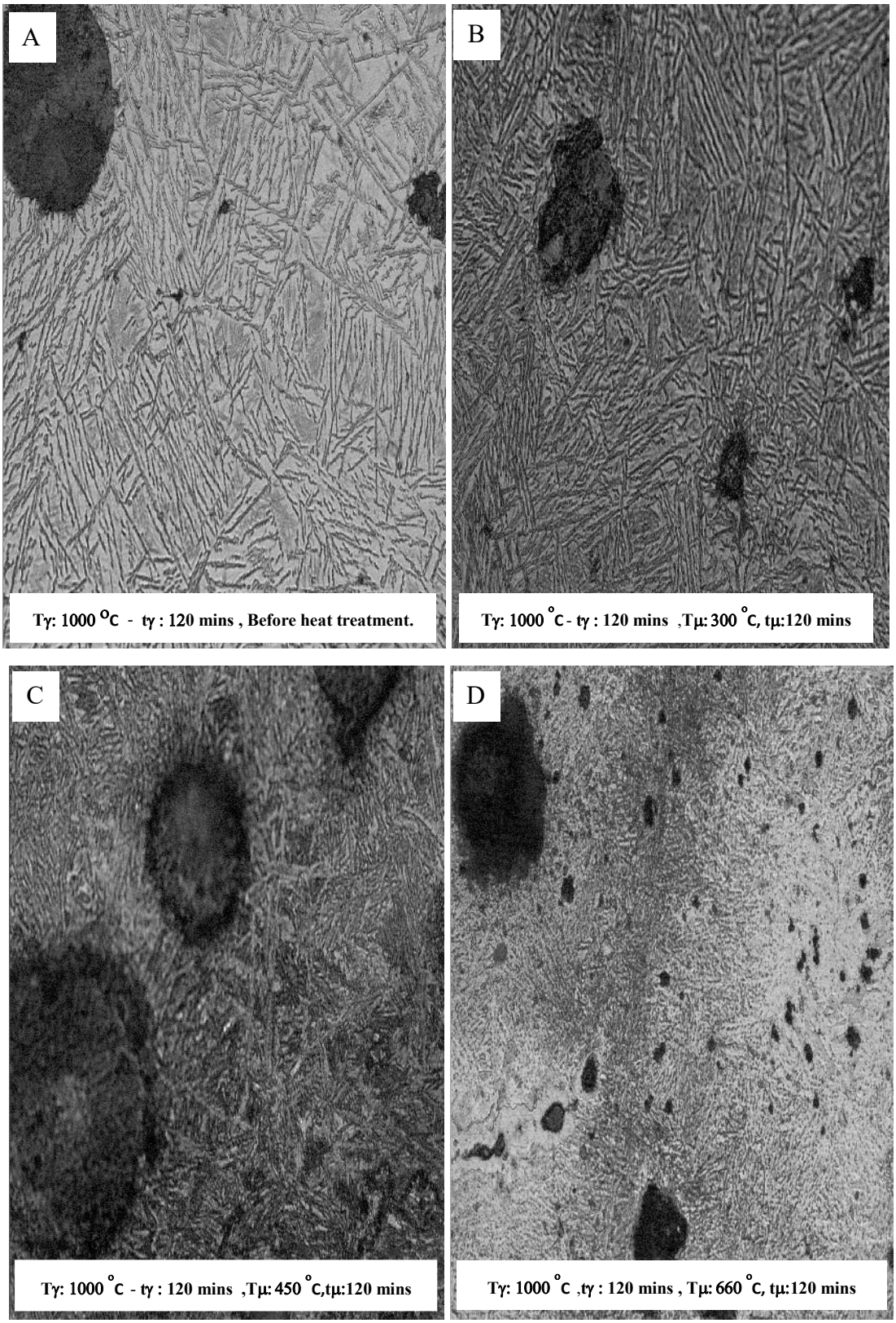


Fig. (5.3): Microstructures of samples before and after tempering at 300, 450 and 660ºC for 120 mins. and austenitized for 120 mins (500x).

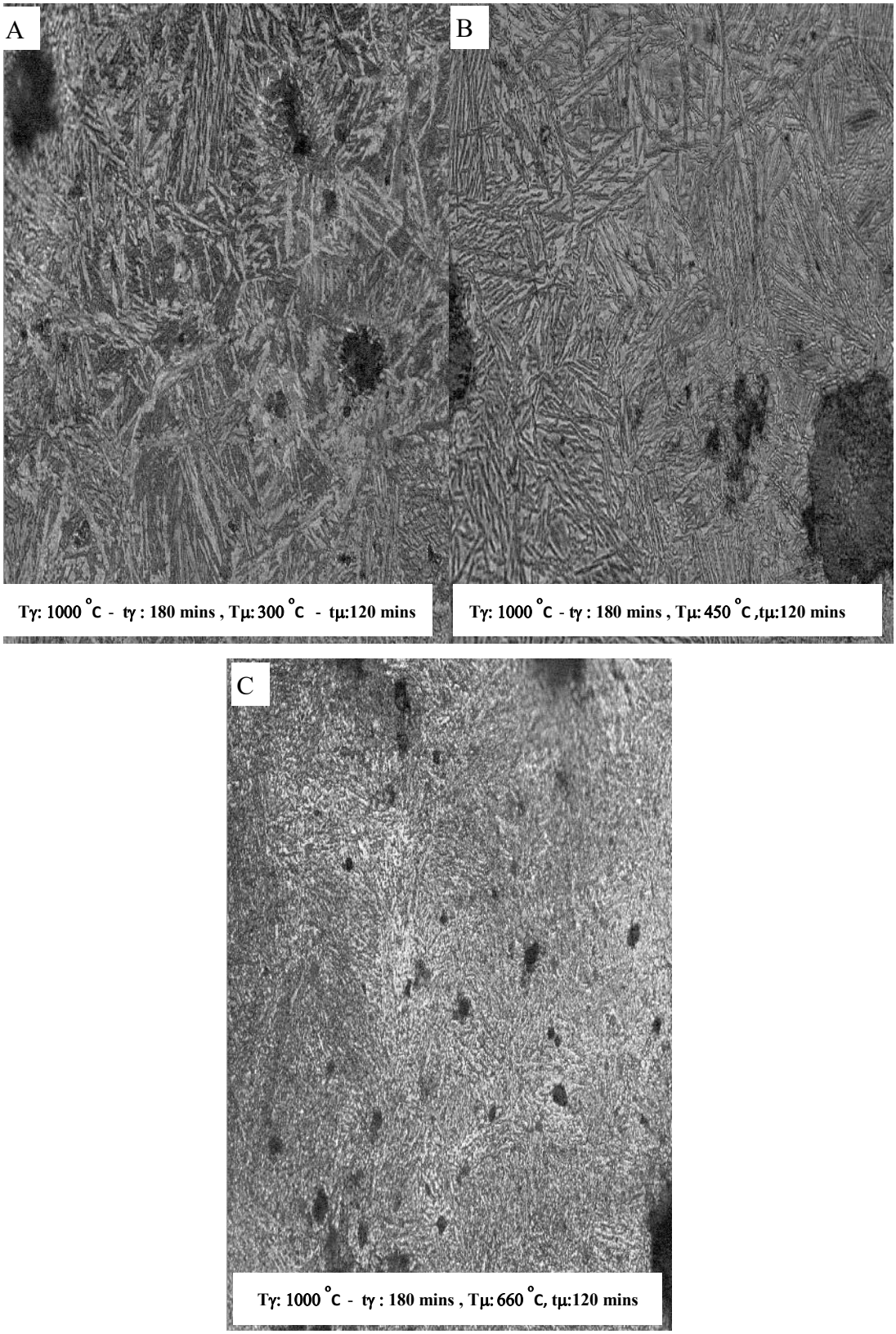


Fig. (5.4) : Microstructures of samples before and after tempering at 300, 450 and 660ºC for 120 mins and austenitized for 180 mins (500X).

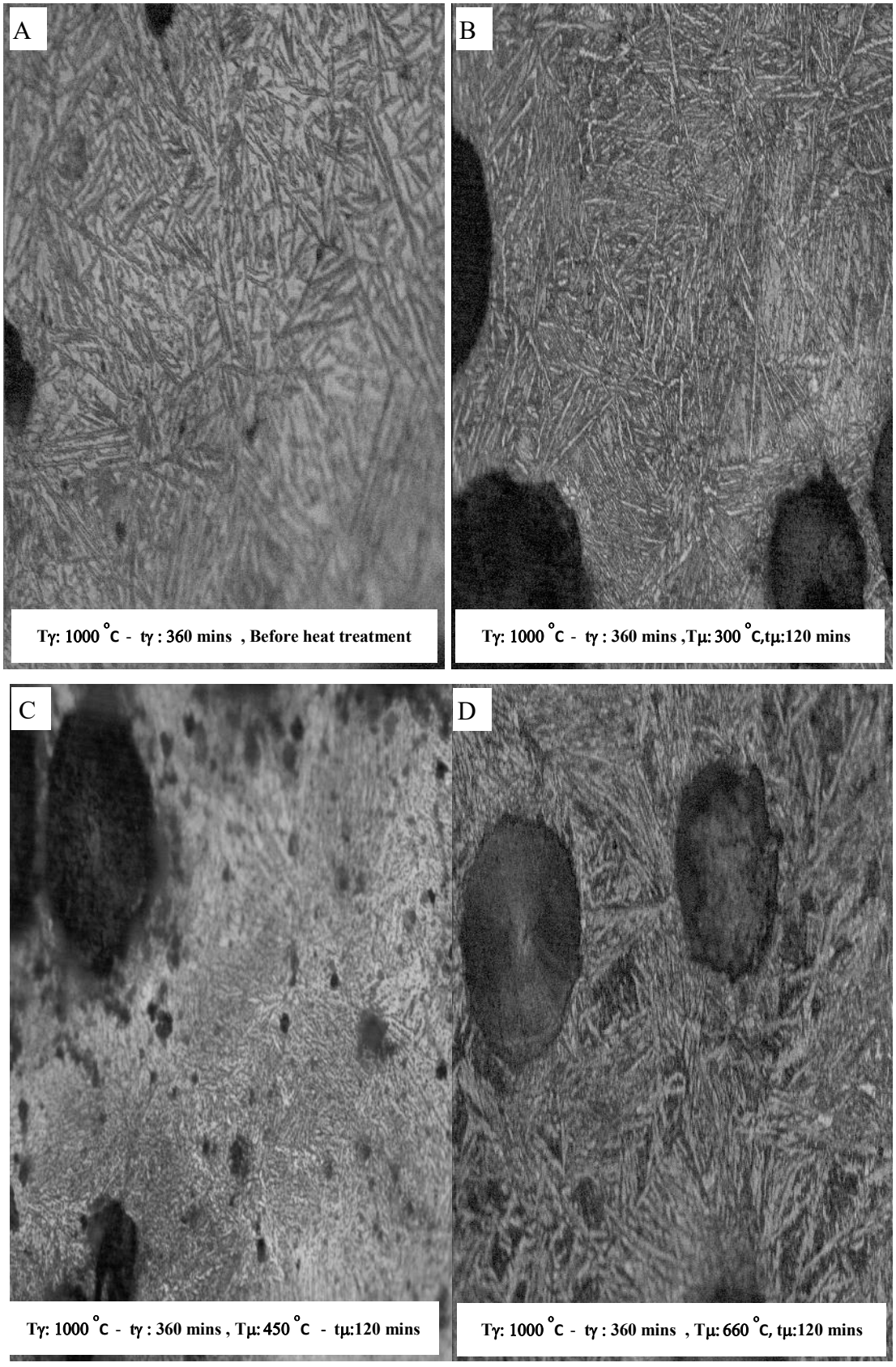


Fig. (5.5): Microstructures of samples before and after tempering at 300, 450 and 660 ºC for 120 mins. and austenitized for 360 mins (500X).

5.3 Effect of Tempering time on the hardness and microstructure of ADI at 450°C

The results of tempering time of ADI samples tempered at 450°C for 90 , 120 and 150 mins. are summarized in tables (4.6, 4.7 and 4.8) and Figures (5-6).
As the tempering time increases the hardness values decrease slightly. It can be concluded that the effect of tempering time has slightly or no effect on the hardness values.

The reduction in hardness is usually accompanied by an increase in ductility, thereby decreasing the brittleness of the metal.
study by A Sidney H [31] shows that, to relieve thermal residual stresses and improve ductility & toughness the tempering treatment can be used. The enhancement in ductility leads to depreciation in the hardness & strenght.
Work by P. Fenech, effect of tempering of ADI. his work included an alloy containing 3.3% C, 2.5%Si, 0.5%Mn and 0.05%Mg shows that ultimate tensile strenght decreased with both tempering time at temperature. The 0.2% proof stress followed the same trend but the corresponding values were lower. On the other hand the elongation and percentage reduction in area increased with tempering time and temperature. In this work hardness values decrease slightly with increasing time.

In this work the tempering is done after austempering treatment and hardness properties were compared with austempered ductile iron.
The hardness values of tempered samples were compared with non-tempered samples. There was significant increase in hadness values of samples tempered for 90, 120 and 150mins. As compared to non tempered austempered ductile iron.

As the tempering time was increased from 90 to 150 mins. there was a slight reduction in hardness values for samples austenitized at 1000°C/120, 180 and 360 mins. In fact, the hardness values of samples austempered for 60, 120, 180 and 360 mins. followed the same trend.

Precise control of time and temperature during the tempering process is critical to achieve the desired balance of hardness propeties [55].

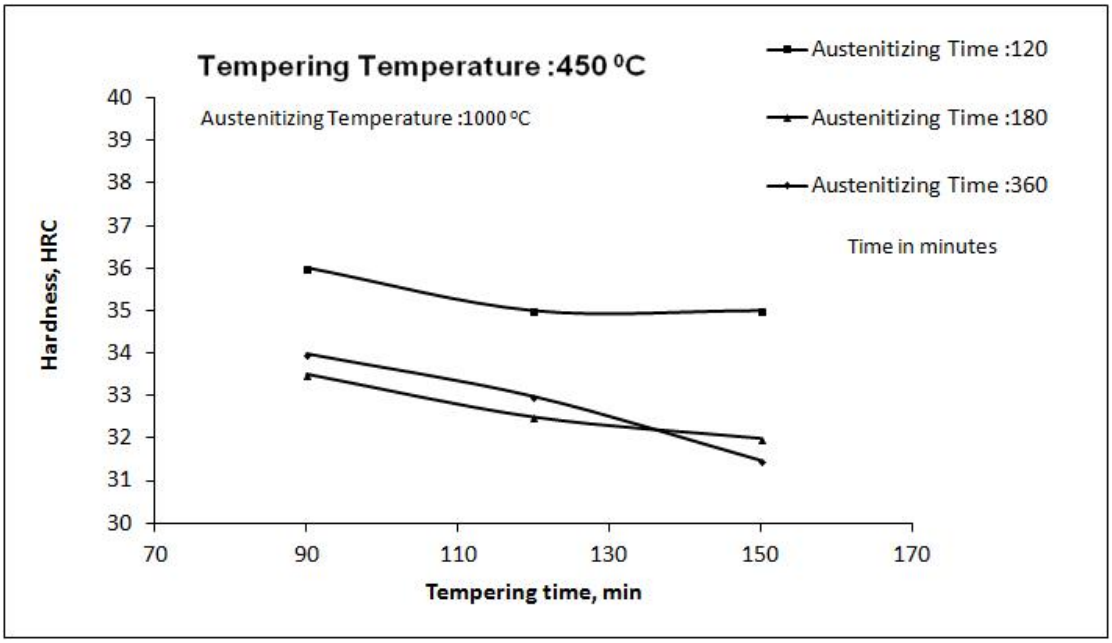


Fig. (5-6) : Effect of Tempering time on the hardness of ADI tempered at 450°C and austenitized for 120, 180 and 360 mins.

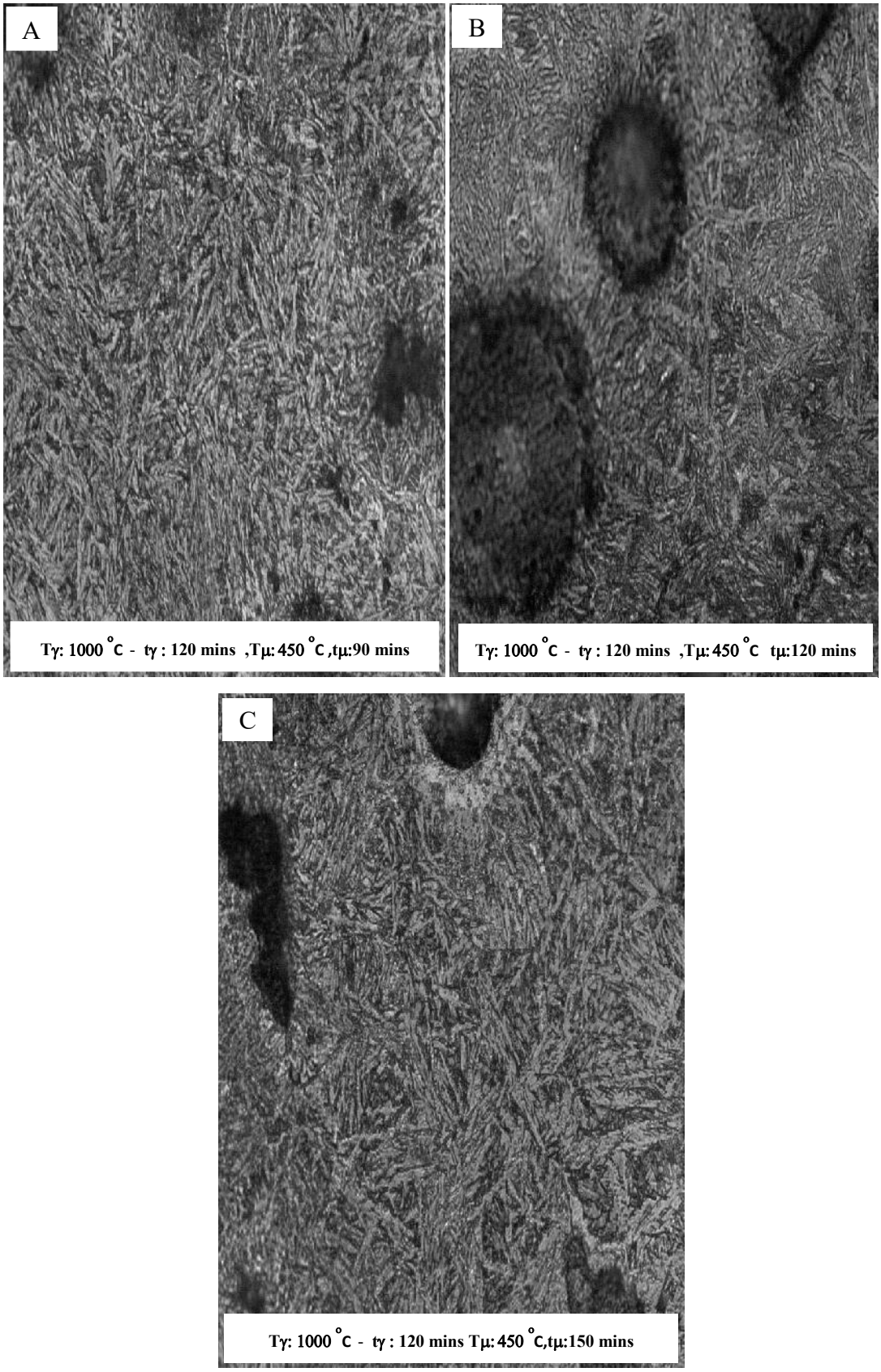


Fig. (5-7) Microstructures of samples after tempering at 450^{O}C for 90, 120 and 150 mins. and austenitizing time 120 mins.

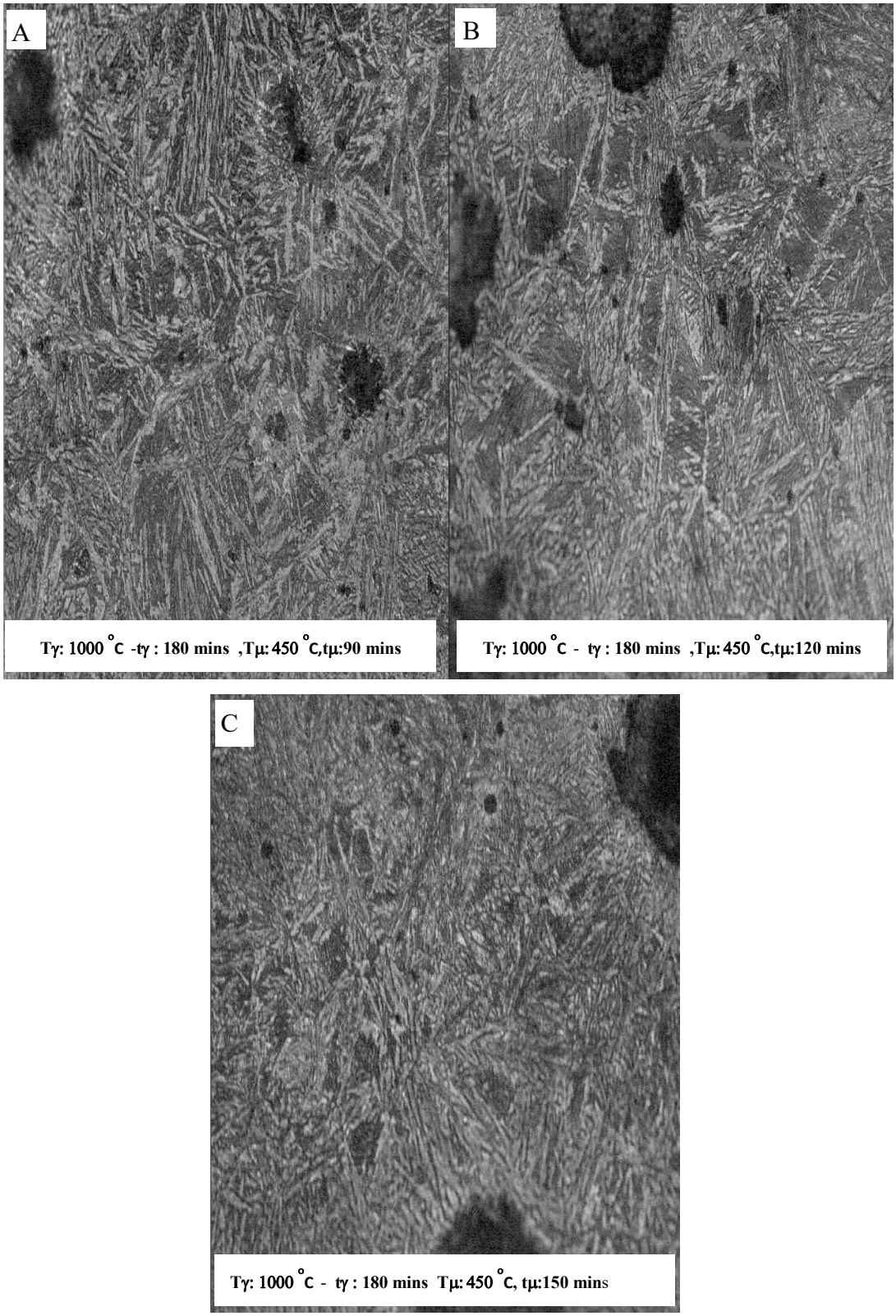


Fig. (5-8) Microstructures of samples after tempering at 450^{O}C for 90, 120 and 150 mins. and austenitizing time 180 mins.

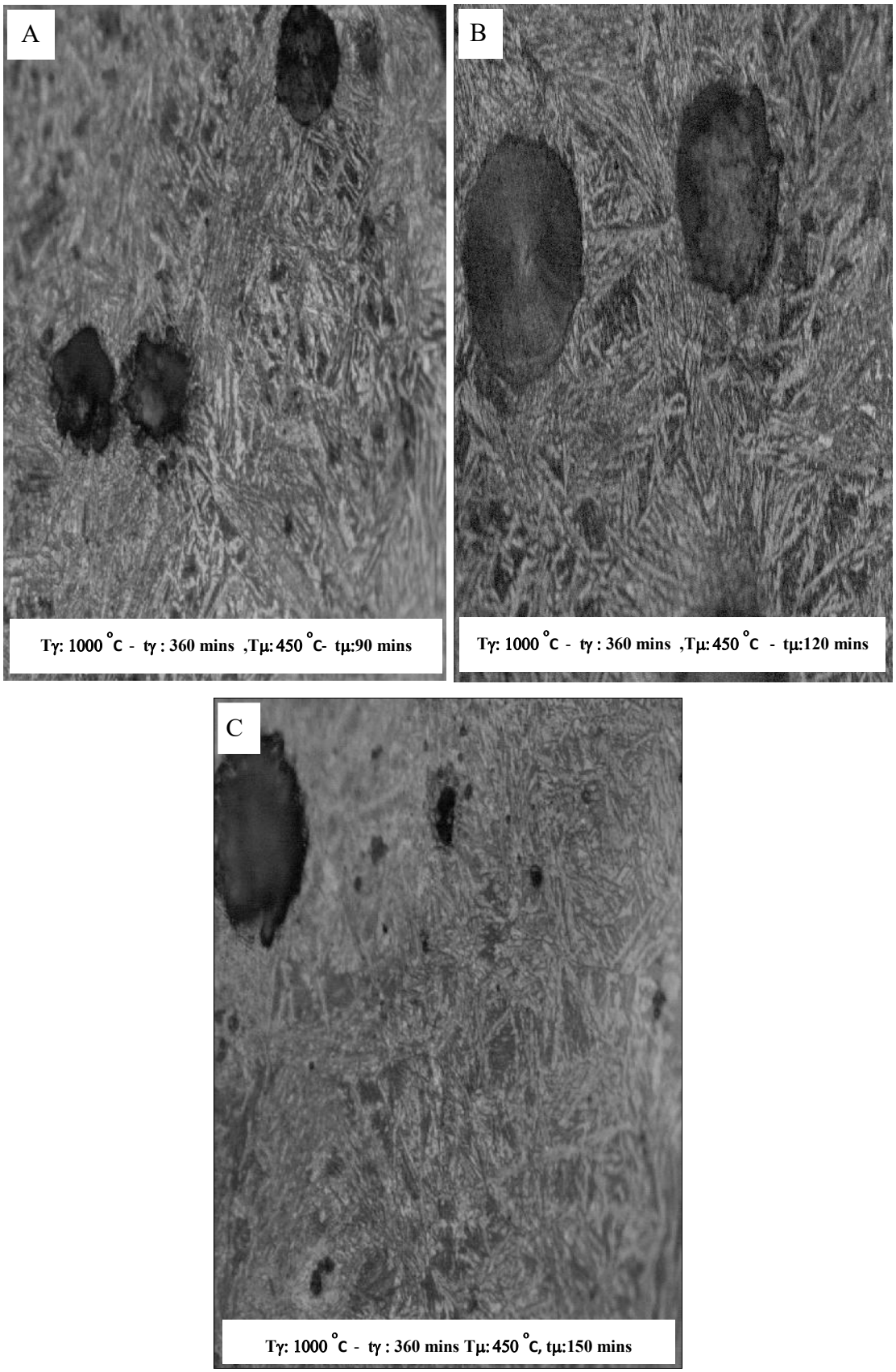


Fig. (5-9) Microstructures of samples after tempering at 450^{O}C for 90, 120 and 150 mins. and austenitizing time 360 mins.

In the study of high strength-steel by Tomita and Okabayashi [60], they have reported the relative variations in mechanical properties of steel having a mixed structure of various types of bainite and tempered martensite. Lower bainite mixed with tempered martensite significantly improved mechanical properties resulting in larger strength and ductility than those of lower bainitic structure alone. However, the mixture of upper bainite and tempered martensite possessed less ductility than that of upper bainitic structure only. Only few attempts have been made to examine the influence of tempered martensite on the mechanical properties of ADI family. ADI microstructure obtained in the work consists of ferrite, martensite and a lot of high carbon austenite. This microstructure is different from that of steel; therefore, the influence of tempered martensite on the mechanical properties of ADI may be different.

CHAPTER 6
CONCLUSIONS, RECOMMENDATIONS AND FUTURE WORK

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The present study has investigated the effect of tempering conditions on the hardness and microstructure of austemperd ductile iron. The change in microstructure and the related changes in hardness have been investigated. The conclusions obtained are as follows.

6.1 THE EFFECT OF TEMPERING TEMPERATURE

- ✓ Increasing the tempering temperture from 300 to 500oC increases the hardness values due to tempered martensite.

- ✓ The tempering process of ADI in the tempering range 300-500^{o}C has hardness values more than ADI samples without tempering.

- ✓ Increasing the tempering temperature beyond 500^{o}C leads to gradual decrease in hardness values. However, the hardness values of ADI tempered at temperatures beyond 550^{o}C are lower than samples without tempering.

- ✓ In general it can be concluded that the hardness value increases with both tempering temperature and time. Optimum hardness values are attained following tempering at 450^{o}C for 120 minutes.

- ✓ Practically, the overall increase in hardness may not be considerable.

6.2 THE EFFECT OF TEMPERING TIME.

- ✓ Tempering for short times (say 90 minutes) at 450ºC have high hardness values compared with longer times.
- ✓ All samples tempered at 450ºC for 90, 120 and 150 mins. have hardness values higher than samples before tempeirng.
- ✓ Tempering time had the same effect on the hardness properties and microstructure as tempering temperature but the effect of the former was less pronounced.
- ✓ It can be concluded that the tempering time has slightly effect on the hardness values.
- ✓ In general, it can be concluded that the hardness decreased slightly with both tempering time and temperature. This result is in agreement with other work carried out by P. Fenech on another alloy.
- ✓ The hardness vary depending upon the various heat treatment processes. Hence depending upon the hardness and applications required a suitable heat treatment processes should be conducted.

6.3 RECOMMENDATIONS AND FUTURE WORK

- ✓ Studying the effect of austenitizing time on the microstructure and the mechanical properties of ADI at different tempering temperatures and times.

- ✓ Studying the effect of annealing process on the this alloy as there was a sharp decrease of the hardness value at the highest tempering temperature.

- ✓ The hardness property should be considered carefully even when its increase is not considerable. The effect of this increase in the industrial field may be studied..

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