

Effect of Heat Treatment Parameters and Alloying Elements on Microstructure of Austempered Ductile Iron – A Review

Sagar A. Patil^{1*}, Sanket S. Vathare²

¹Undergraduate Student, Mechanical Engg., PVPIT Budhgaon

²Head & Assistant Prof, Dept. of Foundry Tech., Vivekanand College, Kolhapur.

Abstract – The most rapidly growing area of cast technology is that of Austempered Ductile Iron (ADI). This paper reviews the effect of alloying elements and heat treatment parameters on microstructure of Austempered Ductile Iron. ADI is a heat treated Ductile Iron or S.G. iron with a unique micro-structure: Ausferrite which consists of high carbon Austenite and Bainitic ferrite with graphite nodules dispersed in it. This is one of the unique microstructures having excellent properties: high strength, toughness, good wear resistance, good machinability and all that at low cost. The use of this type of cast iron as an engineering material has been increasing day by day since its discovery. These properties can be achieved upon adequate heat treatment which yields optimum microstructure for a given chemical composition. But this type of treatment is bit tricky, since it requires controlled heating and isothermal holding of the material. In this work an investigation has been conducted on ductile iron with and without Copper additions and austempered in a range of time and temperature. The influence of conditions of isothermal heat treatment on microstructure and mechanical properties of austempered ductile iron, especially different temperature of isothermal transformation of austenite and different holding time at this temperature, is shown in the paper.

Keywords: ADI, Austempering, Ausferrite, Elongation, Toughness.

INTRODUCTION

The material which offers design engineer the best combination of low cost, design flexibility, good machinability, high strength to weight ratio & good toughness, wear resistance is Austempered Ductile Iron (ADI) [2]. Austempered Ductile Irons are an interesting class of materials because of their unique microstructure and interesting properties. When subjected to austempering treatment, ductile iron transforms to a microstructure consisting of ferrite and stabilized austenite rather than ferrite and carbide as in austempered steels. Technical literature oftendescribes this matrix as bainite (although it does not contain carbides) [2] [7]. The matrix is also referred to as ausferrite microstructure (high carbon austenite + ferrite) [14]. The structure of Austempered Ductile Iron is obtained by exactly controlled process of heat treatment of nodular cast iron. Because of the presence of stabilized austenite, ADI exhibits excellent combination of strength and ductility, together with good fatigue and wear properties [1] [8]. Compared to the conventional grades of Ductile Iron, ADI delivers twice the strength for a given level of ductility in the form of elongation. But achieving excellent mechanical

properties of the ADI material is not an easy task as they depend on austempered microstructure which is a function of its processing window [4]. The optimum combination of high carbon austenite and bainitic ferrite of ADI makes it possible to compete against steel forgings and other engineering alloys in terms of mechanical properties, physical properties, weight saving and all that at low cost [14]. ADI offers superior combination of properties because it can be cast like any other member of the ductile iron family, thus offering all the production advantages of a conventional ductile iron casting [6] [18]. The ductile iron casting subsequently subjected to the austempering process to produce mechanical properties that are superior to conventional ductile iron and forged steel [15] [19]. Due to its vast area of applications, extensive work is being carried out now-a-days to study the processing and characterization of this material [14] [19].

A. The ADI Process

To produce ADI, ductile iron must undergo austempering process. While the steps for austempering ductile Iron are essentially the same as

those for steel, the resultant microstructure is different. It is called ausferrite and consists of a mixture of high carbon austenite and ferrite [17]. Austempering process consists of following-

- Heating to a temperature to produce austenite.
- Quenching rapidly to avoid pearlite formation or martensite. The quench temperature is called as austempering temperature.
- Holding at the selected austempering temperature for a time sufficient to transform the austenite to the desired end product; bainite for steel and ausferrite for ductile iron[9][19].

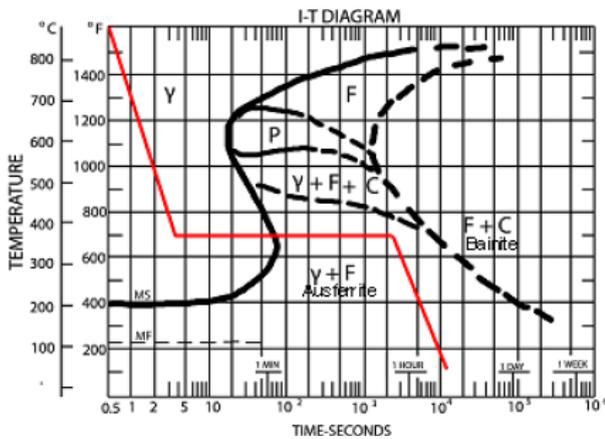


Fig. 1. An isothermal transformation diagram that shows the basic steps of austempering process for cast iron [17].

EXPERIMENTAL PROCEDURE

Experimental material was cast in the electric induction furnace. The basic charge was formed by pig iron, steel scrap and additives for the control of chemical composition. FeSiMg7 modifier was used for modification and FeSi75 inoculant was used for inoculation [7].

Ferrite-pearlitic nodular cast iron was used as basic material for isothermal heat treatment. The austenitization temperature was 920°C and the holding time at this temperature was 30 minutes. The isothermal transformation of austenite was realized in AS 140 salt bath at the temperatures 420, 380, 320 and 250 °C and the holding time at this temperature was from 30 to 300 minutes (by 30 min. step)[9][14]. Preparation of cast iron specimens is difficult due to the need to properly retain the graphite phase. The specimens were subjected to coarse grinding using motor driven emery belt. Coarse grinding is required to planarize the specimen and to reduce the damage created by sectioning. The planar grinding step is accomplished by decreasing the abrasive grit/ particle sizes sequentially to obtain surface finishes that are ready for polishing. The machine

parameters, which effect the preparation of metallographic specimens, should be taken care of, for example grinding/polishing pressure, speed, and the direction of grinding/polishing. The other steps were rough polishing using abrasive papers of successively finer grades. In order to ensure that the previous rough grinding damage is removed when grinding by hand, the specimen should be rotated 90 degrees and continually ground until all the scratches from the previous grinding direction are removed. If necessary the abrasive paper can be replaced with a newer paper to increase cutting rates. Then fine polishing was done in a cloth polishing mill using aluminum powder as polishing agent. The purpose of final polishing is to remove only surface damage. It should not be used to remove any damage remaining from cutting and planar grinding. If the damage from these steps is not complete, the rough polishing step should be repeated. Finally the samples were etched for microstructure study. The purpose of etching is to optically enhance micro-structural features such as grain size and phase features. Etching selectively alters these micro-structural features based on composition, stress, or crystal structure. The most common technique for etching is selective chemical etching. Chemical etching selectively attacks specific micro-structural features. Here etchant used was nital (2% conc. Nitric acid in methanol solution) and washed thoroughly and dried. Then the microstructures were taken for different heat treated specimens using Scanning Electron Microscopy (SEM) with required magnifications [4][6].

RESULTS AND DISCUSSION

From the microstructural point of view the basic material (after casting) is ferrite-pearlitic nodular cast iron (Fig. 2) with 57% content of ferrite in a matrix, the size of graphite within 15 and 60 μm and count of graphitic nodules 205 mm². Graphite occurs only in a perfectly-nodular (80%) and imperfectly-nodular (20%) shape [14].

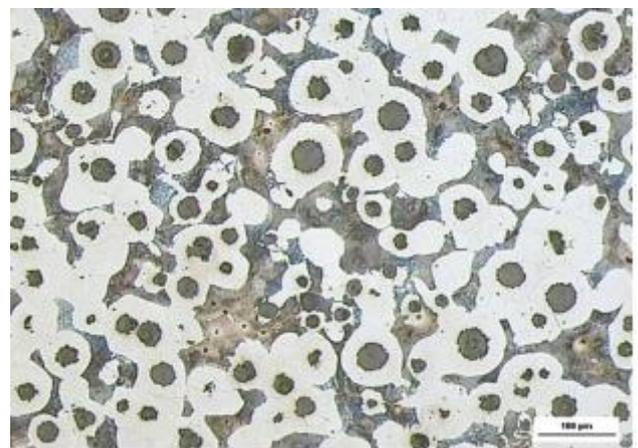
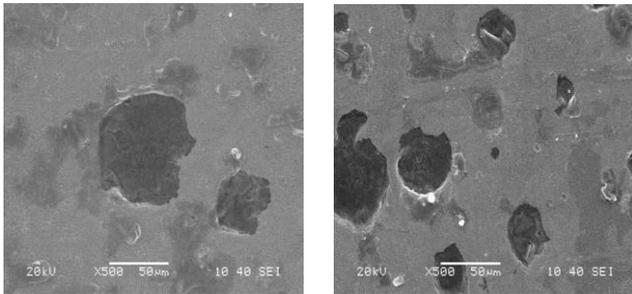


Fig. 2. Microstructure of basic material (after casting) – ferrite-pearlitic nodular cast iron [14]

The microstructures of ductile iron samples with and without copper austempered at 350°C were studied under scanning electron microscope with 550X magnification.



(a) Without copper

(b) With copper.

Fig 3. SEM microstructures of ADI tempered at 350°C for 1.5 hrs [13].

As seen in Fig.3 the heat-treated microstructures of both materials consist of graphite nodules of different sizes in the matrix phase. From the microstructures it was seen that copper addition does not cause any observable change to the austempered microstructure of plain ADI. In some cases the copper is associated with the graphite nodules, but not necessarily as a thin film [13].

A. Microstructure of ADI

ADI is a heat treated Ductile Iron with a unique microstructure consisting of Ausferrite which consists of high carbon Austenite and Bainitic ferrite with graphite nodules dispersed in it. ADI is a ductile iron that has been heat treated by the austempering process to make it tougher than regular ductile iron of half the strength. ADI is comparable in strength to heat treated wrought steels, has exceptional wear and fatigue resistance and has the ability to be work hardened [10][16]. As 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 [6][20].

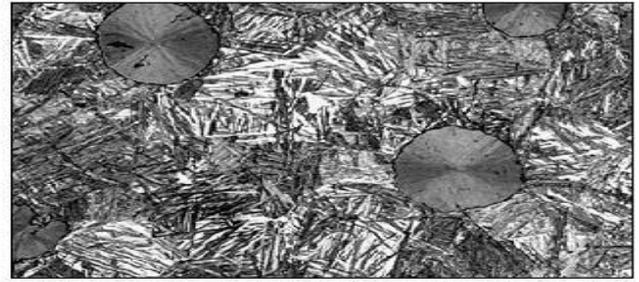


Fig. 4. ADI microstructure consists of acicular ferrite in high carbon austenite matrix called ausferrite [6].

The content of retained austenite is slightly decreased with increasing holding time in all sets of specimens. The shape, size and count of graphite nodules in the specimens after isothermal heat treatment are not changed in comparison with the specimen of basic material (after casting)[10][14].



Fig. 5. Microstructure of specimen after isothermal heat treatment – 380°C/ 60', ADI – matrix created by upper bainite and retained austenite [14].

The austenitizing temperature should be chosen so that the component is in the austenite + graphite ($\gamma + G$) phase field. Elements like Silicon raise the UCT while Manganese will lower it. If the austenitizing temperature is below the UCT or in the subcritical range ($\gamma + \alpha + G$), then proeutectoid ferrite will be present in the final microstructure, resulting in a lower strength and hardness material. Once the ferrite forms, the only way to eliminate it is to reheat above the UCT. Fig.6 shows the microstructure of an austempered material that was austenitized below the UCT [19].

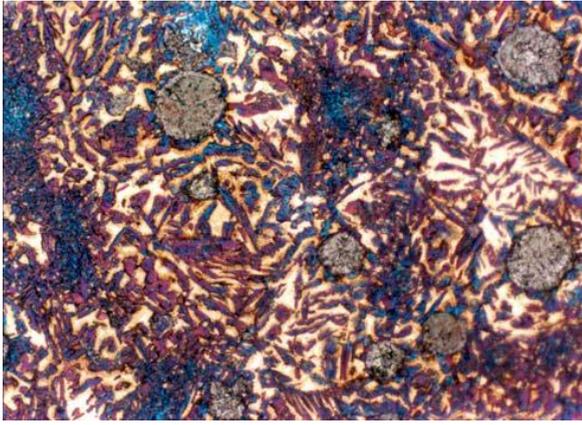
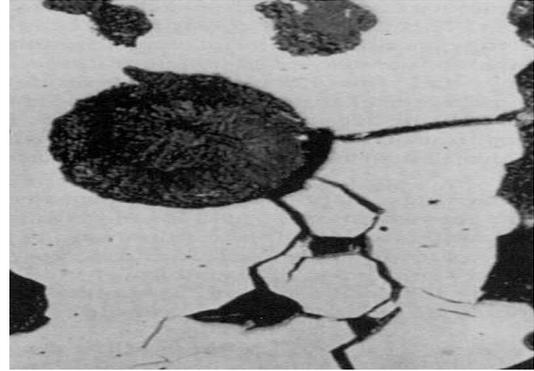


Fig.6.A photomicrograph of ADI that was austenitized below the upper critical temperature (UCT).the light regions are ferrite [19].



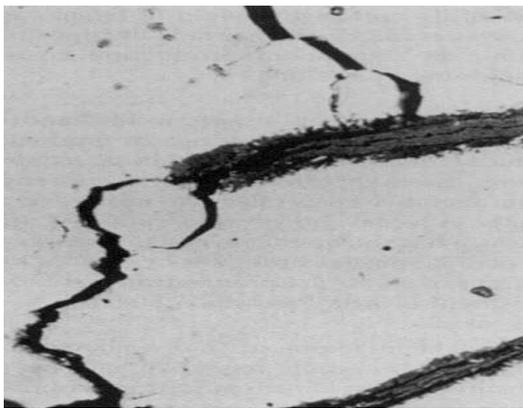
(b)

Fig.7.Different forms of graphite [3].

B. Graphite in ADI

Graphite 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. The compact spheroid interrupts the continuity of matrix much less than graphite flake and this result in higher strength and toughness compared with a similar structure of gray cast iron [3].

Fig.7 (a) and (b) show that graphite flakes act like cracks in the iron matrix, while graphite spheroids act like “crack arresters”, giving the respective irons dramatically different mechanical properties [3].



(a)

In iron-carbon alloys, though graphite is more stable phase than cementite but kinetically, it is easier to produce cementite than graphite. When graphite forms directly from the liquid, it is called primary graphitization, but when the graphite forms from the dissociation of cementite, it is called second stage graphitization. The formation of graphite from liquid takes place in a narrow range of temperature interval (1153-1147°C for plain carbon) and also the formation of graphite from austenite (738-727°C), i.e., under the condition of small under cooling. This requires the alloy to be cooled slowly [5].

Nucleation of graphite requires much more energy and large amount of diffusion of carbon to the nuclei and iron atoms away from it to get 100% carbon to segregate. So formation of graphite from liquid in pure iron-carbon alloy is almost a rare reaction, unless the factors for graphite formation are favorable. Commercial cast iron melt always contains fine particles of inclusion, even particles of graphite. Nucleation of graphite on some of these inclusions needs less energy than that required for nucleation of cementite and thus graphite crystal can be formed kinetically even at temperatures below 1147°C [10]. Graphite thus can form not only from liquid or austenite (738-727°C), the metastable cementite under favorable conditions, such as high temperatures can decompose to austenite + graphite (above 738°C) or ferrite + graphite (below 738°C). The former is a faster process, but complete graphitization does not occur as 0.68% C remains dissolved in austenite, whereas the latter is the slower process, but complete graphitization occurs [11] [16].

C. Effect of Alloying Elements in ADI

The alloying elements that are typically added for hardenability purposes include: Cu, Ni and Mo. Manganese additions are not recommended because of the tendency of Mn to segregate to the regions in between the graphite nodules. Manganese delays the austempering reaction, which can result in the

formation of martensite due to the presence of low carbon austenite [19].

Nickel and Copper segregate to graphite nodule sites and do not form detrimental carbides [5]. According to the experimental work of P. W. Shelton, A. A. Bonner [12] and Olivera Eric [13] alloying with copper increases elongation and impact energy but decreases the strength of ADI. As shown in Fig. 8, it was seen that a straight forward addition of copper to a conventionally produced and heat treated ADI had not produced the well defined copper coated graphite nodules those were hoped for. In some cases the copper was associated with graphite nodules, but not as a thin film. There were also isolated pools of copper present in the microstructure comparable in size with graphite. The distribution and size of graphite spheroids was similar however for both the materials, with no evidence that the copper addition influenced either. Where there was porosity, a concave graphite surface or irregularity in the shape of the graphite nodule, the copper was often attracted to those features [18].

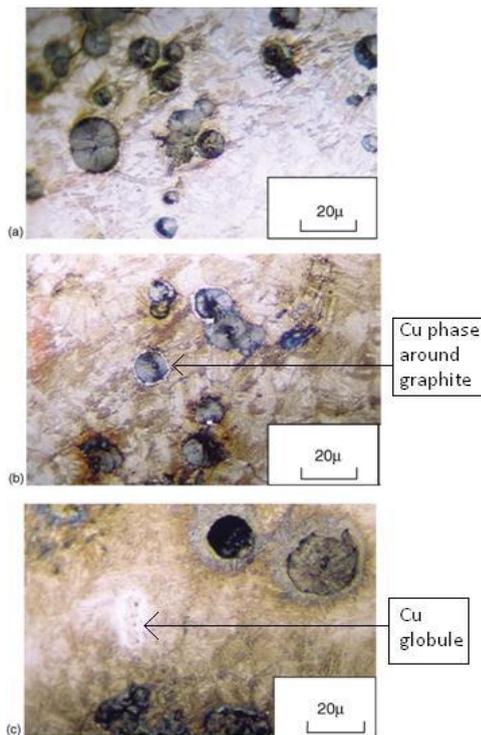


Fig.8. Austempered microstructures, etched in 2% nital. (a) Plain ADI austenitized at 940°C and austempered at 320°C. (b) Copper enriched ADI austenitized at 900°C and austempered at 290°C, showing nodules with copper-rich phase around all, or part of graphite nodule. (c) Copper enriched ADI austenitized at 940°C and austempered at 320°C showing a discrete copper globule, left of centre [13].

Nickel additions are made when the level of Cu has been maximized. Ni additions of up to 2 % are typically made. Beyond that, the price becomes an important consideration. Lastly, Molybdenum is a potent hardenability agent. Unfortunately, it segregates highly to the intercellular/interdendritic locations between the graphite nodules. Molybdenum is strong carbide former. Fig.9 shows a photomicrograph of Molybdenum carbides that were present in ADI with a Mo addition. The formation of Mo carbides is undesirable, especially if a component is to be machined after heat treatment [19].

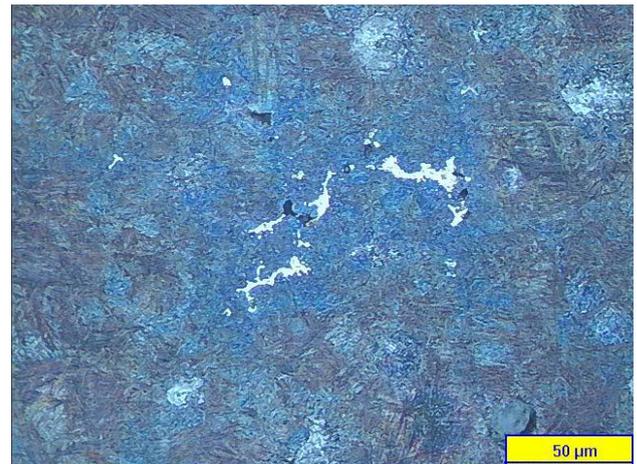


Fig.9. Molybdenum carbides (white) in ADI [19].

CONCLUSION

From the study of microstructure of properties of austempered ductile iron the following conclusions could be drawn-

1. The specimens with higher temperature of isothermal transformation of austenite have the matrix created by upper bainite and retained austenite and the specimens with lower temperature of isothermal transformation of austenite have the matrix created by lower bainite and retained austenite.
2. The content of retained austenite is decreased with increasing holding time at the temperature of isothermal transformation.
3. The shape, size and count of graphitic nodules are not changed in dependence on the temperature of isothermal transformation of austenite and independence on the holding time at this temperature.

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Corresponding Author

Sagar A. Patil*

Undergraduate student, Mechanical Engg., PVPIT Budhgaon

E-Mail – sagarpatil2808@gmail.com