Effect of Austempering Time and Temperature on Structure and Properties of Unalloyed Ductile Iron

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Abstract

Austempered ductile irons are characterized by a combination of high tensile and fatigue strength, ductility and wear resistance combined with impact toughness. However, the use of these irons has been limited due to lack of metallurgical knowledge available to show how the excellent properties of austempered irons can be obtained consistently in production; and identifying and controlling the heat treatment parameters to obtain optimum properties. There is also insufficient data available to the design engineers identifying the full engineering properties of bainitic irons. Using indigenously available raw materials, a detailed investigation was carried out with unalloyed ductile iron to produce austempered ductile iron. It was found possible to produce austempered unalloyed iron with consistent properties by suitable austenitising and austempering treatments. The structure and properties of these irons were studied and correlated with the process parameters such as austempering temperature and time and compared with the as-cast structure and properties.

Key words: Austempered Ductile Iron, Bainitic Ferrite, Austenite, Temperature, Microstructure, Mechanical Properties, As-Cast

1. Introduction

Austempered Ductile Iron (ADI) provides the design engineer with a family of materials with a combination of strength, ductility and wear resistance not available in conventional grades of ductile iron. Thereby providing a basis for widening the existing design limits for ductile iron itself

and also for competing with steel forgings (Cox 1982), (Dodd 1978), (Edvard 1986). Austempered Ductile Iron has an exceptionally high strength-to-weight ratio with good fatigue strength and fracture toughness. The density of ductile iron is 10% less than that of steel so ADI parts can replace steel forgings and castings at a weight saving (Hayrynen *et al*, 2002). In addition, with strenght three times greater than that of aluminium with only two and a half times the density, ADI can replace aluminium of equal weight for a substantial cost saving. ADI casting is finding increasing use in automotive, agricultural and machine tool industries (Roun *et al*, 1984).

The isothermal formation of bainitic ferrite is termed the austempering process. Austempering leads to a final microstructure, which is a mixture of high-carbon retained austenite with bainitic ferrite distributed throughout, depending on the temperature employed (Chang, 2003). The principal matrix structure obtained in ADI is a combination of bainitic ferrite and high carbon stabilised austenite. Appearance of bainitic structure changes with temperature and two distinct bainitic morphologies are apparent. Bainite formed at lower austempering temperature is stronger and harder but less ductile (Breeden 1983a). Two separate bainite reactions results can occur during austempering. The first reaction results in the formation of bainite-austenite structure, which is very tough. The second reaction results in a reduction in toughness or embrittlement, and occurs with extended time at the austempering temperature. Thus there is a finite range of austempering times for obtaining high toughness ductile irons having high strength (Breeden 1983b). Unalloyed ductile irons require critical control of composition and heat treatment parameters for consistent results with austempering.

2. Major Variables

The properties of austempered ductile irons are dependent on four major variables, namely: - (i) chemical composition (ii) section size (iii) austenitising temperature and time, and (iv) austempering temperature and time.

Austenitising temperature (Thomson *et al*, 2000) generally used is in the range of 850°C to 950°C. It significantly influences transformation during austempering through its effect on dissolved carbon content. Increasing the temperature, the solubility of carbon and thus the amount of carbon dissolved in austenite is increased. As dissolve carbon content increases, the amount of austenite remaining at the end of the first reaction also increases. Matrix carbon content is not only

determined by austenitising temperature and chemical composition but also by time and temperature (Sandwich 1982a), (Sandwich 1982b).

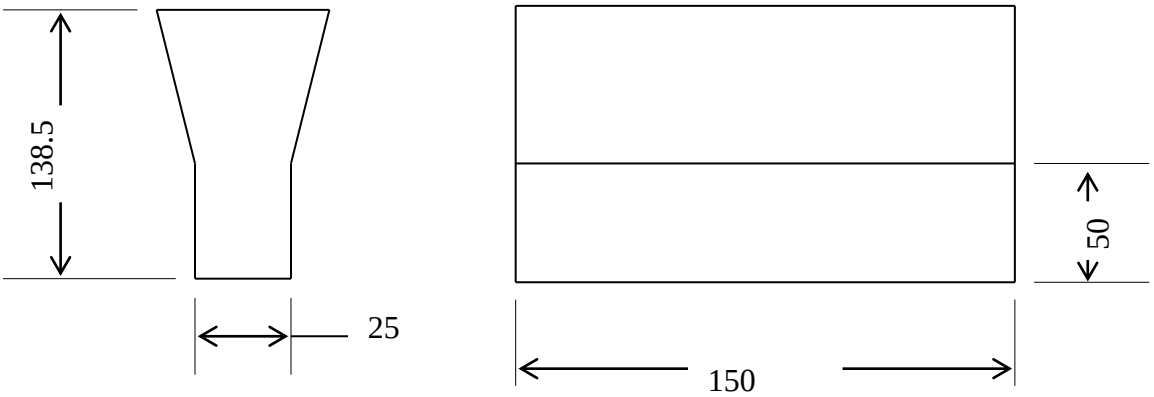
While a fully pearlitic iron containing substantial combined carbon will reach a uniform carbon content in less than 30 minutes, ferritic iron requires significantly more time to reach equilibrium carbon content. Mechanical properties, machining, work hardening and stability of austenite are likely to be strongly influenced by the austenitising temperature (Rao and Putatunda, 1998) through its control of matrix carbon. Individual alloying elements will increase or decrease matrix carbon and likewise have an effect on the rate and degree of bainitic reactions, thereby influencing the final microstructure and properties (Bosnjak *et al*, 2000). Austenitising time also plays significant role for quality production of ductile iron. Long holding times may lead to increased surface oxidation and grain growth whereas too short a holding time may results in incomplete austenitisation (Wen and Lei, 1999). The general rule of thumb is to hold it for one hour at the austenitising temperature for 25 mm casting thickness.

The morphology of bainite and the quantity of retained austenite and martensite is mainly governed by the austempering temperature and time. Austempering is normally (Kozsely and Tranta, 2003) carried out in the range 230°C – 450°C. Upper bainite is formed when austempering is carried out above 330°C and lower bainite results when austempering is done below 330°C. Austempering time is also important and generally it is varied from ½ hour to 2 hours. At longer times strength is unaffected while ductility is progressively reduced due to reduction in retained austenite.

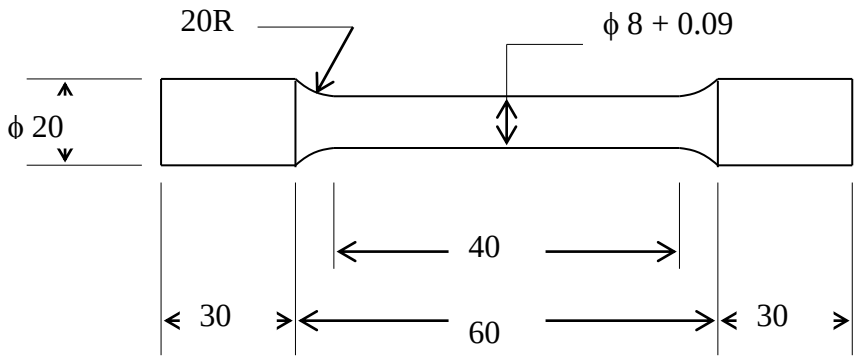
Ductile iron production in the developing countries is nominal compared to other developed countries (Karsay 1965). Some of the main reasons for low production in developing countries are higher contents as S, P and Mn in the pig iron and very high ash content in the coke. Some of the Indian producers of ductile iron have to adopt a long route of production by melting steel and adjusting the composition in the furnace by carburisation, addition of Si in the form of Fe-Si, etc. for the ductile iron. As a result the cost of production is considerably increased. In the present work, a detailed investigation was carried out to produce ductile iron using indigenously available pig iron and to study the influence of austempering temperature and time on the structure and mechanical properties of unalloyed ductile iron.

3. Experimental Details

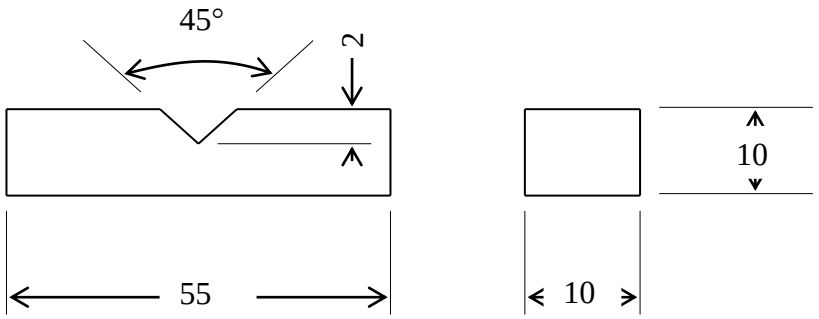
Several heats of ductile iron were produced in a single-phase arc furnace of 20kg capacity with nominal carbon and silicon contents of 3.5 and 1.7-weight per-cent respectively.



Y - BLOCK



TENSILE TEST SPECIMEN



IMPACT TEST SPECIMEN

Figure 1: Dimensions of Y-Block and Specimen for Tensile and Impact Tests

The charge consisted of indigenously available pig iron and returns. Crushed graphite electrodes in granular form were added for carburisation to adjust the carbon content and ferro-silicon (65% Si) was added for raising the silicon content of the melt. The melt was desulphurised in the furnace using 1.5% of calcium carbide.

In each heat the sandwich technique was used to treat 16kg of iron with 7.4-weight percent ferro-silicon-magnesium alloy. Standard Y-blocks of dimensions given in Figure 1 were poured in green sand mould at about 1380°C. The charge make up for each heat is given in Table 1.

Table 1. Description of Different Melts Taken.

Heat No.	Pig iron charged, kg	Fe-Si added, gms	Graphite added, gms	Calcium carbide for desulphurisation, gms	Fe-Si-Mg alloy, gms
1	15	370	50	225	360 (7.4% Mg)
2	15	210	50	225	360 (7.4% Mg)
3	20	165	50	300	450 (7.4% Mg)
4	20	165	50	300	450 (7.4% Mg)
5	20	165	50	300	450 (7.4% Mg)
6	20	165	50	300	450 (7.4% Mg)

Specimens for hardness, tensile strength and impact tests were cut from the Y-blocks. The location of tensile and impact specimens and their dimensions are shown in Figure 1.

Heat treatment of the specimens was done by austenitising the specimens in the muffle furnace. Austenitising temperature was kept constant at 900°C for 1½ hour. All specimens were heat treated in a bed of cast iron chips to minimize decarburisation. Austempering was carried out at one of the temperatures 300, 350, and 400°C by quenching in salt bath and holding at temperature for a range of times (30, 75, 120 and 165 minutes). After austempering specimens were cooled in air.

Hardness (Brinell), tensile and impact tests were done in the as-cast as well as heat treated conditions. Specimens for metallography were prepared in the normal way and microstructures were studied using optical as well as scanning electron microscope (JEOL, JSM-840A).

4. Results and Discussion

A study of the microstructure and properties of the iron confirmed that good quality ductile iron could be produced using indigenously available pig iron. The average properties of the iron thus produced are: UTS- 55 kg/mm^2; Impact Strength – 0.60 kg-m; Nodule Count – 160 per mm^2.

4.1 Effect of Austempering Temperature on Structure and Mechanical Properties

4.1.1 Microstructure

Samples for micro-examination in the as-cast and heat-treated conditions were prepared from the broken tensile test pieces. Initially the samples were observed under optical microscope and then using Scanning Electron Microscope. All the photomicrographs shown were taken using SEM.

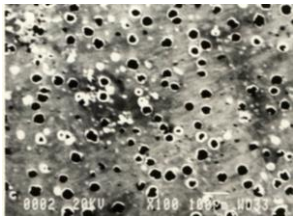


Figure 2: Photomicrograph of As-cast Ductile Iron (×40)

The microstructure of as-cast ductile iron is shown in Figure 2. It is observed from this microstructure that the nodules are quite uniform in size and are uniformly distributed throughout the matrix. Similar structures were observed for all the samples taken from different heats in the as-cast condition.

(a) (b) (c)

Figure 3: Micrographs of Ductile Iron Austempered at 900°C for 1 ½ hours and Austempered for 30 minutes at (a) 300°C (b) 350°C (c) 400°C (× 400)

From the study of the photomicrographs of austempered ductile iron shown in Figure 3, it is evident that the matrix consists mainly of acicular bainite. It is also observed that the bainite becomes coarser with increasing austempering temperature. Fine acicular bainite structure is observed at 300°C, coarse at 350°C and coarser at 400°C. The microstructure at the higher temperature of 400°C reveals the presence of austenitic regions indicating the transition from lower bainite to upper bainite region.

4.1.2 Mechanical Properties

4.1.2.1 Hardness

The influence of austempering temperature on hardness is shown in Figure 4. It is found that the hardness decreases with increasing austempering temperature. The decrease in hardness is attributed to the increase in retained austenite with increasing austempering temperature confirmed earlier by microstructure examination.

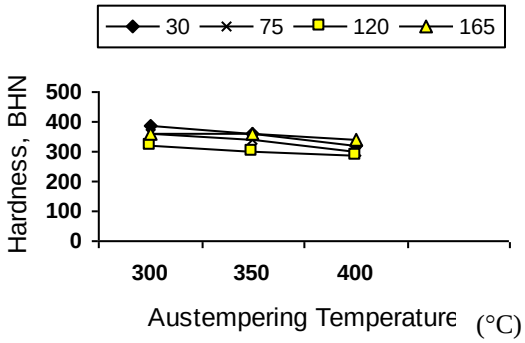


Figure 4: Variation of Hardness with Austempering Temperature for given Austempering Times (30, 75, 120 and 165 mins)

4.1.2.2 Ultimate Tensile Strength

The variation of ultimate tensile strength with austempering temperature is given in Figure 5. Ultimate tensile strength decreased from 132 kg/mm^2 to 119.2 kg/mm^2 with increasing austempering temperature from 300°C to 400°C. The higher strength at lower temperature is attributed to the fineness of the bainite structure. With the interlamellar spacing decreasing, hindrance to the dislocation movement will be more and crack initiation and growth will be slow. In

addition to fineness of the structure, the fine secondary carbides formed help in dispersion strengthening of the matrix.

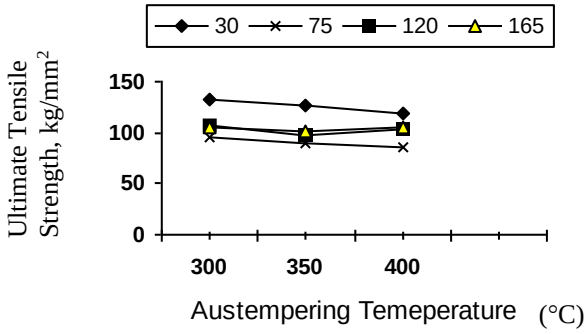


Figure 5: Variation of U.T.S. with Austempering Temperature for given Austempering Times (30, 75, 120 and 165 mins)

4.1.2.3 Impact Strength

The variation of charpy V-notch impact strength with increasing austempering temperature is also given in Figure 6.

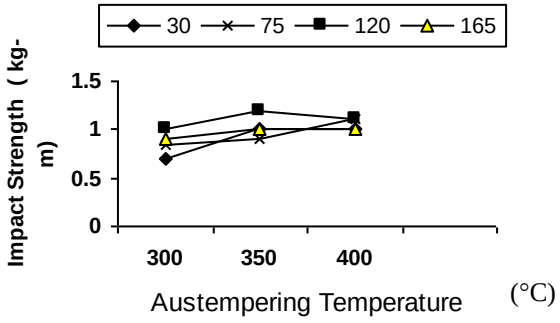


Figure 6: Variation of Impact Strength with Austempering Temperature for given Austempering Times (30, 75, 120 & 165 mins)

It is obvious from this Table that the impact strength increases with austempering temperature. Sample austempered at 300°C for 30 minutes gave the impact strength of 0.7 kg-m and it increased to 1.1 kg-m with austempering temperature increased to 400°C. The impact strength of S.G. iron sample austempered at 300°C (0.7 kg-m) is marginally higher than as-cast S.G. iron (0.6 kg-m). The impact strength of sample austempered at 400°C is nearly double compared to the impact strength

of as-cast S.G. iron. The increase in impact strength is attributed to the increase in the percentage of austenite with increase in austempering temperature since austenite increases the toughness of the phase. Therefore for those castings requiring higher impact strength one has to austemper at a high temperature, say 400°C.

4.2 Effect of Austempering Time on Structure and Properties

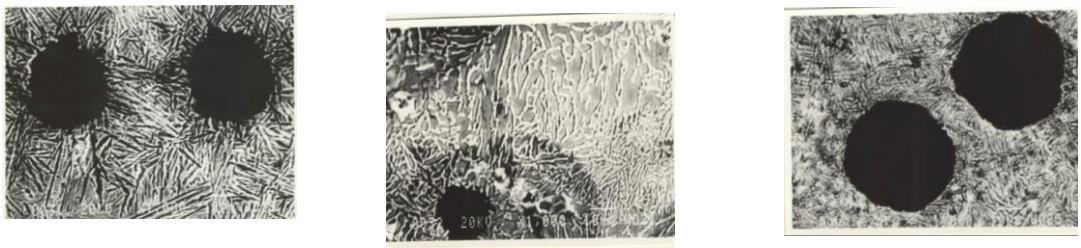
The effect of austempering time was studied by austempering samples at 300°C, 350°C and 400°C for different periods of time (30 mins, 75 mins, 120 mins and 165 mins) at each of these temperatures. All the samples were austenitised at 900°C for one and half-hours.

4.2.1 Microstructure

Microstructure of samples austempered at 300°C, 350°C and 400°C for different periods of time are shown in Figures 7 to 9. Microstructures of specimens austempered up to 75 minutes do not show much variation among each other.

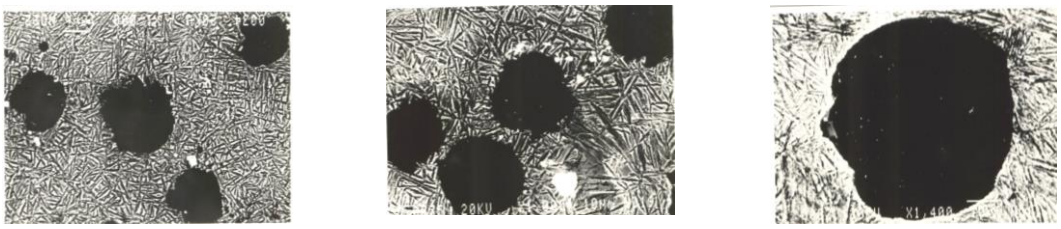
(a) (b) (c)

Figure 7: Scanning Electron Micrographs of Ductile Iron Austempered at 300°C for (a) 75 mins (b) 120 mins (c) 165 mins (×400)



(a) (b) (c)

Figure 8: Scanning Electron Micrographs of Ductile Iron Austempered at 350°C for (a) 75 mins (b) 120 mins (c) 165 mins (×400)



(a) ×400 (b) ×400 (c) ×560

Figure 9: Scanning Electron Micrographs of Ductile Iron Austempered at 300°C for (a) 75 mins (b) 120 mins (c) 165 mins (×400)

The specimen austempered for 120 minutes shows significant increase in retained austenite. Further, the specimens austempered for 165 minutes show fine and lower bainite. This shows that the samples austempered for 120 minutes seem to represent condition of completion of first stage reaction and the samples austempered for 165 minutes show less amount of retained austenite, which indicates the onset of second stage reaction.

4.2.2 Mechanical Properties

4.2.2.1 Hardness

A graph showing the relation between hardness and austempering time is shown in Figure 10.

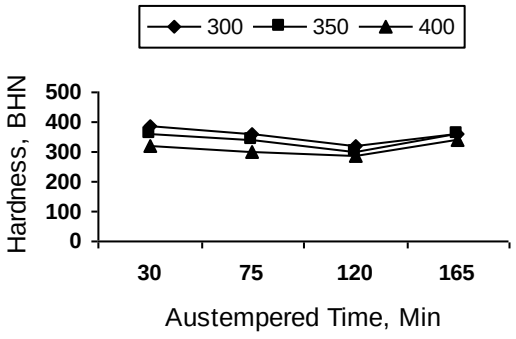


Figure 10: Effect of Austempering Time on Hardness for given Austempering Temperatures (300°C, 350°C and 400°C)

Hardness is relatively high after austempering at 300°C for half an hour. Hardness reduces gradually and then increases with increasing austempering time. This may be due to the presence of martensite at lesser times. As the time increases martensite content decreases and bainite content increases. At the end, the increase in hardness is attributed to the presence of precipitated carbide.

4.2.2.2 Ultimate Tensile Strength

The variation of ultimate tensile strength with austempering time is also shown in Figure 11. It is observed that the ultimate tensile strength decreases with increase in austempering time up to 75 minutes and then increases gradually. This trend can be attributed to the presence of martensite content at lower times.

With increase in the time martensite content decreases and bainite content increases. Further increase in time results in gradual increase in tensile strength, which may be attributed to the precipitation of fine carbides throughout the matrix.

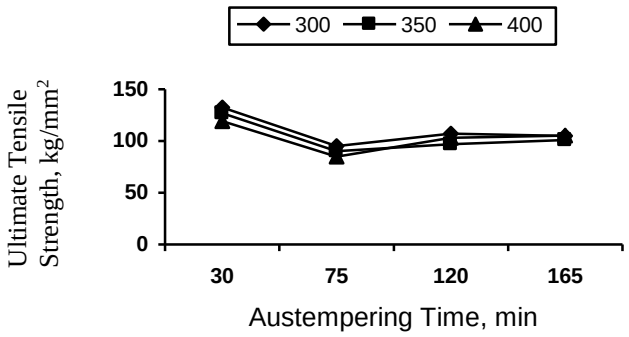


Figure 11: Effect of Austempering Time on U.T.S. for given Austempering Temperatures (300°C, 350°C and 400°C)

It can be noted that there is more than two fold increase in tensile strength of as-cast S.G. iron by austempering for half an hour at any of the temperatures investigated. Therefore castings requiring high strength but lower ductility should be austempered for shorter period whereas good combination of strength and ductility are desired, the austempering should be done at higher temperature and for longer period (75 to 100 minutes) of time.

4.2.2.3 Impact Strength

The variation of impact strength with austempering time is also shown in Figure 12. Impact strength increases as the austempering time increases up to 120 minutes and decreases gradually. This may be due to the increase of retained austenite with increasing time and the fall in impact strength at the end is attributed to the precipitation of carbide phase from austenite. This confirms the presence of brittle phase for longer and shorter times than the optimum time.

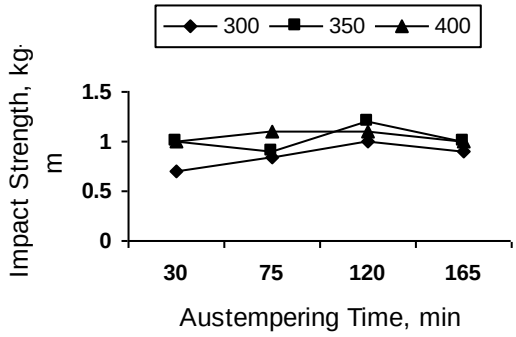


Figure 12: Effect of Austempering Time on Impact Strength for given Austempering Temperatures (300°C, 350°C and 400°C)

5. Conclusion

From the results of investigation carried out to produce austempered ductile iron using indigenously available pig iron, it can be concluded that: -

(i) Austempered ductile iron can be successfully produced by suitable austenitising and austempering treatments of unalloyed ductile iron.

(ii) A two-fold increase in ultimate tensile strength or impact strength of as-cast ductile iron can be easily obtained by proper control of austempering time and temperature.

(iii) For high strength and hardness, one can select a low austempering temperature and time (say at 300°C for 30 minutes for the iron investigated)

(iv) For castings requiring high impact strength and ductility, the austempering should be carried out at intermediate temperature (viz. 350°C) for 1 ½ to 2 hours.

(v) Elongation and impact toughness vary with austempering time, so that for each austempering time a minimum time is required to ensure a desired elongation.

(vi) Achievement of maximum toughness and reproducibility of mechanical properties require good nodularity and freedom from intercellular carbides and microporosity.

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