

HEAT TREATMENT OF CAST IRONS

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Heat treatment in a general way improves and alters the heat treating objects. The improvements are aimed in respect of mechanical properties, machinability, homogeneity, relieving of stresses, hardening and others. The application of heat causes certain structural changes in the object responding to subsequent improvements in the properties.

CAST IRON - CHARACTERISTICS

The ferrous metals, steel or cast irons are essentially an alloy of iron and carbon. The cast iron contains carbon ranging from 2 to 4%, with the element silicon playing a most important role. Silicon influences the eutectic carbon content of Fe - C alloy and with presence of silicon eutectic carbon is estimated as:

$$\text{Eutectic carbon \%} = 4.25 - 0.30 \times (\% \text{Si})$$

In cast iron, the carbon is present in two forms. A stable form shows carbon is present as free graphite and an unstable form indicates presence of carbon in a combined form (cementite, Fe_3C). Grey cast irons are characterised by the presence of all or most of the carbon in the form of graphite, white cast irons are characterised by the presence of all the carbon in combined form, i.e., in the form of cementite. An iron of borderline composition which freezes partly as a white iron and partly as a grey iron under prevailing conditions of cooling is termed as mottled iron. Two more types of cast irons are also widely accepted as separate class owing to their achieved property. Thus, malleable cast iron derives its name from its ability to bend or undergo permanent deformation before it fractures. Malleable cast iron is produced by heat-treating (malleablizing) a white iron casting. The structure indicates presence of

temper carbon nodules in a matrix of pearlite or ferrite. The spheroidal graphite (S.G. iron) or ductile iron shows the presence of graphite in form of spheroids rather than as flakes. The graphite modification is brought in by treating a melt of grey iron composition (low S, low P) with a small percentage of magnesium, cerium or other nodularising agents.

The carbon content in the matrix of grey iron is usually about 1%, which is with the exception of the graphite, is composed of an alloy of iron and carbon. For the majority of grey iron castings the most typical structure is either composed of graphite, ferrite and pearlite (ferrite - pearlitic) or of graphite and pearlite (pearlitic). Cast iron with a structure of graphite and ferrite (ferritic) is very soft, weak and possesses a low resistance to wear, whereas that with a structure of graphite, pearlite and cementite is very hard and difficult to machine.

The factors which influence the character of the carbon are:

- a) the rate of cooling,
- b) the chemical composition,
- c) the presence of nuclei of graphite and other substances

A high rate of cooling tends to prevent the formation of graphite, promoting chilling. Fig. 1 shows a relationship between the rate of cooling and hardness in a varying sections of thickness.

The grey irons are usually analysed for C, Si, S, P, Mn as constituents. Carbon lowers the melting point of the metal and produces more graphite. Silicon slightly strengthens the ferrite and act as a graphitiser by increasing the tendency of the cementite to split up into graphite and ferrite. Fig. 2 shows the relation between the carbon and silicon contents in producing different irons for one rate of cooling. Sulphur remains in the melt either in the form of FeS (iron sulphide) or MnS (manganese sulphide). Sulphur in the form of FeS tends to promote cementite. In presence of Mn, however MnS or complex manganese-iron-sulphides forms which begin to precipitate early and continue to do so during entire freezing process and are therefore usually randomly distributed. The effect of Mn alone is to promote resistance to graphitisation. Thus, Mn above that necessary to react with the sulphur will help in retaining the pearlitic microstructure. In view of attaining desired microstructure, the sulphur-manganese relationship is expressed as below:

- a) $\% S \times 1.7 = \% Mn$; Chemically equivalent S and Mn percentage to form MnS considering no effect from iron,
- b) $\% S \times 1.7 + 0.15 = \% Mn$; the Mn percentage which will promote a maximum of ferrite and a minimum of pearlite,
- c) $\% S \times 3 + 0.35 = \% Mn$; the manganese percentage which will develop a pearlitic microstructure.

Phosphorus practically does not influence the graphite - cementite ratio. It often occurs as steadite, a eutectic of iron and iron phosphide of low melting point. In the production of sound castings of heavy sections, phosphorus should be reduced to about 0.3% in order to avoid shrinkage porosity.

The chemical constituents of the melt particularly silicon and phosphorus affect the composition of the eutectic point, which is at 4.3% carbon for a Fe - C alloy. The influence of these elements in to carbon replacement values is expressed as *carbon equivalent* and is accepted as an index to predict the closeness of a given composition of iron to the eutectic. Fig. 3 depicts CE value, section size, tensile strength and microstructure relationship.

Of the alloying elements, nickel, akin to silicon, dissolves completely in ferrite, also acts as a graphitizer while the carbide forming elements, specifically chromium and molybdenum, tend to stabilize the carbide phase. Thus, by adding these elements in proper relative quantities, the graphitizing characteristics of the original unalloyed cast iron will be relatively unaffected.

Presence of graphite nuclei at the time of solidification promote solidification directly as graphite. Superheating destroys these graphitic nuclei and induce greater undercooling. Since the γ -Fe₃C eutectic temperature is a few degrees below the γ -graphite eutectic, the undercooled liquid solidifies according to metastable system. A high silicon and carbon, however, induces immediate subsequent graphitization. Inoculation of the superheated iron may permit attainment of the normal and usually more desirable graphite structure, i.e., flakes having uniform distribution and random orientation.

The eutectic solidification, thus, follows the reaction:

liquid $\rightarrow$ austenite + Fe_3C or liquid $\rightarrow$ austenite + graphite depending on the cooling rate, chemical constituents and presence of graphite nuclei. In a condition of superheating and resulting undercooling effect, another reaction is anticipated:

Liquid $\rightarrow \gamma + \text{Fe}_3\text{C}$ then $\text{Fe}_3\text{C} - \gamma + \text{graphite}$.

The resulting microstructures in these cases show the interdendritic graphite flakes having either random or preferred orientation.

CAST IRONS - HEAT TREATMENT

Grey Iron

Grey irons are amenable to normal heat treatments applied to steel as the metallic matrix of the grey irons is considered as steel. Thus improvement in machinability, strength, dimension stability is achieved through heat treatments involving stress-relief annealing, annealing, hardening and tempering.

Stress-Relief: Castings are sometimes found to change dimensions to a considerable extent. Such dimensional changes are due to residual stresses in the castings arising in the casting process resulting from non-uniform cooling. To remove any of the residual internal stresses present and to soften any hard spots and hard corners resulting from chill, castings are subjected to a stress-relief annealing treatment.

A specific stress-relief-anneal consists of heating slowly (at the rate of 100 to 150°C per hour) to a temperature between 500 and 600°C. At this temperature the castings are maintained for a period of 3 to 5 hours, after which they are slowly cooled (at a rate of 25 to 75°C per hour) to a temperature of between 150 and 250°C. The treatment allows the castings to be finish-machined to desired dimensions without warping. The treatment also improves machinability of the casting as hard spots are softened due to breaking down of combined carbon.

Annealing: In order to improve the machinability, grey irons are annealed. The high hardness in grey iron is attributed to the presence of combined carbon. To decrease the hardness and improve the machinability grey irons are annealed by means of heating to a temperature of between 850 to 950°C and holding at that temperature for a period of 1 to 2 hours and then in most cases cooled in the open air. The thin sectioned castings,

however, are liable to warping, the degree of deformation increasing with the annealing temperature. In those cases, the castings are annealed at comparatively lower temperature of 800 to 850°C with the holding time considerably lengthen. Castings are then cooled in the furnace upto a temperature of 400 to 500°C, with subsequent air cooling.

Hardening and Tempering: The castings which require a high wear resistance are subjected to hardening with subsequent tempering. The pearlite in the structure of the iron can be changed to austenite upon heating to above critical temperature of the iron, and, upon rapid cooling (quenching), transformed to martensite. The casting thus treated can be tempered to relieve the quenching stresses, increase the toughness of the iron, and reduce the maximum hardness. In the process, the castings are heated for hardening upto a temperature ranging between 800-900°C, the lower limit being selected for intricately shaped articles and the higher one for articles of simple design. The cooling is also performed differently - casting of simple shape may be quenched in water, and those of more intricate design, in oil. The hardened castings are tempered at a temperature between 350 to 450°C for a period of 1 hour.

The strength of the grey iron castings are more influenced by the size, shape and distribution of the graphite flakes rather than the properties of the matrix. In fact, graphite flakes interrupt the continuity of the metallic matrix. A high hardness developed in the metallic matrix by means of a heat treatment is thus offset by the graphite present. The otherway of imparting strength to the grey iron is by way of changing the graphite morphology and thus malleable, ductile and high strength cast irons have been developed.

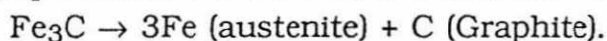
Malleable Iron

Malleable cast irons are produced in two stages, first one involves production of white iron castings and second stage involving high temperature annealing of these castings. Malleable cast irons are characterised having all their graphites in the form of nodules and exhibit considerable higher mechanical properties compared to grey iron.

The usual chemical composition of heat treatable white irons for malleable iron production consists of C-2.0 to 2.8 Si 0.9-1.30, Mn < 0.60, P < 0.20, S < 0.18. The structure consists massive carbide and pearlite.

The purpose of malleablization is to convert all of the combined carbon into elemental carbon (graphite) and ferrite. This conversion, in usual practice, is a two step process commonly referred to as first and second stages of the graphitization (Fig. 4 & Fig. 5). The first stage of a typical heat treating cycle consists in heating the castings at a temperature between 900 to 950°C. The pearlite transforms into austenite by a process of rapid diffusion of the carbon from cementite into the iron to form a solid solution of carbon in gamma iron. The massive carbides are virtually unaffected by heating. Therefore, above the eutectoid range (but below the eutectic) the iron consists of massive carbides in austenite.

When white iron castings of malleable composition are held at elevated temperatures, particularly those above the eutectoid or critical range, graphitization of the massive carbides will occur as follows:



After the first stage of graphitisation, the structure of a malleable cast iron consists of austenite and graphite. If malleable iron is cooled after the first stage of graphitisation, its structure will then consists of graphite, pearlite and secondary cementite or ferrite depending upon the cooling rate. The presence of cementite is completely inadmissible, and pearlite, too, is considered undesirable in most cases. The second stage of annealing is intended to decompose both the secondary cementite and pearlite.

The second stage of annealing is performed at the pearlitic transformation temperatures (760-720°C). In this range three phases co-exist; austenite-ferrite-cementite (metastable) or austenite-ferrite-graphite (stable). Because of the very low solubility of carbon in austenite in this range, during a slow rate of cooling through this range graphitization proceeds in accordance with the stable system. If the rate of cooling is otherwise fast, so that graphitization is not completed, the reaction will proceed metastably and cementite will be rejected in the form of pearlite. At a temperature only slightly below the critical range, this pearlite will eventually graphitize, but at an extremely slow rate.

Once an iron has been fully graphitized on slow passage through the critical temperature zone, no further structural changes take place at lower temperatures. Therefore, cooling to room temperature may be at any rate that is feasible.

The temperature employed for malleablization are sufficiently high to induce extensive scaling and decarburisation if the castings are left exposed to normal room atmospheres during the treatment. Therefore, preventive steps are taken in commercial practice by sealing the castings from the air or by surrounding them with a controlled artificial atmosphere that will minimize or eliminate scaling or decarburisation. The workpiece may be sealed through packing the castings in closed pots mudded with fireclay. Depending upon the packing materials, two processes are in use. In a whiteheart malleable process castings are packed in boxes with a mixture of used and new hematite ore. As a result, a portion of the carbon is oxidised leaving in thin sections, a ferritic structure, while in thick sections the edge of the castings is ferritic, and gradually changes to a steel-like structure of ferrite and pearlite, with interspersed nodules of graphite. In a blackheart process the castings are annealed in a neutral packing or atmosphere, consequently little oxidation of carbon occurs. But due to careful balance of the silicon and sulphur contents the cementite breaks down to carbon aggregates in ferrite.

For rapid anneability it is desirable to have higher nodule counts. A number of means increases nodule count such as:

- (i) A fine dispersion of massive carbides in the white iron which is obtained by rapidly cooling the mould.
- (ii) Prebaking the casting between 340°C and 425°C before heating to first stage graphitization temperature. Further nucleation has been effective from heating, after this low temperature prebake, to 650°C , for a brief time and then cooling to room temperature before proceeding with regular malleablizing cycle.
- (iii) Using an initially high first-stage temperature. While such high temperatures will increase the number of nodules, yet, a longer holding time will result in elongated graphite. If held just under the eutectic, typical flake graphite forms. These high temperatures are not conducive to good mechanical properties.
- (iv) Prestressing the white iron before malleablising.
- (v) Alloying/inoculating the melt with graphitizers, such as Si, Al, or B.

Nodular Cast Irons

Nodular irons may be heat-treated for one of the following reasons:

- (a) to produce matrix structure in accordance to achieve desired mechanical properties for the different grades of nodular iron.
- (b) to graphitize carbides which may be present as a result of poor inoculation, incorrect composition or segregation in the heat affected zone of welds.
- (c) to improve the surface wear and/or friction characteristics.
- (d) to improve machinability.
- (e) to effect stress relief.

In order to achieve desired properties, nodular cast irons are subjected to annealing, normalising, hardening and tempering and stress-relieving heat treatment.

Annealing of nodular iron:

Castings are subjected to annealing in view of achieving maximum ductility and best machinability when high strength is not much of a criterion. In the process, the microstructure is being converted to ferrite and spheroidal graphite. The typical cycle involves holding at 920°C for 2 hours and then furnace cooling to 500°C from there on cooled in air.

Normalising of nodular iron

The major objective of normalising heat treatment is to obtain uniform mechanical properties. The treatment produces a homogeneous structure of fine pearlite, if the metal is not too high in silicon and has at least a moderate manganese content. Usually castings with high hardness and residual carbides are subjected to this treatment to improve machinability without compromising the mechanical properties. Normalising is commonly followed by tempering to reduce hardness and relieve residual stresses that develop when various parts of a casting are cooled in air at different rates.

The following two heat treatment cycles are most popular:

- (i) Normalise - 920°C, 2 hours - Air Cool; Temper - 680°C to 710°C, 2 to 4 hours.
- (ii) Step Normalise - 920°C, 2 hours; furnace cool to 800°C hold for 30 minutes; furnace cool to 500°C - hold for 30 minutes.

Hardening and tempering of nodular iron

The main objective of this treatment is to achieve improved wear resistance property. In the process, a temperature of 920°C is normally employed for austenizing commercial castings and produces the highest as-quenched hardness. Oil is preferred as a quenching medium, to minimize stresses. The tempering is carried on between 680°C and 710°C with holding for 2 to 4 hours.

Austempered ductile iron

The austempered ductile iron emerged as a new class of ductile iron owing to the remarkable combination of properties attainable in austempered iron. Austempered ductile iron can be twice as strong as the standard ductile iron grade at the same level of toughness and ductility. In addition they respond to workhardening treatment at the surface leading to high bending fatigue and wear resistance. Specific application include automotive gears and crankshaft.

Austempered ductile irons are prepared from alloyed nodular irons. The alloy combinations are either 0.3% Mo and 1.5% Ni or a combination of 0.5% Mo and 1.4% Cu. The properties are attained by heating to suitable austenising temperature followed by quenching into a medium which is maintained at a constant temperature in the bainitic transformation temperature range (205-400°C) and holding for the time required for transformation to occur. A schematic representation of austempering treatment and cycle is shown in Fig. 6 & 7.

The desired matrix structure of austempered ductile iron consists of a two phase mixture of acicular (or bainitic) ferrite austenite. During austempering bainitic ferrites nucleates and grow into austenite. At the same time carbon is rejected from growing ferrite platelets into the surrounding austenite. The high silicon content of the ductile iron suppress the formation of cementite phase normally associated with bainitic transformation, consequently the remaining austenite continues to absorb carbon as reaction proceeds.

As austenite becomes enriched with carbon, the growth of ferrite platelets are inhibited and the reaction is temporarily arrested. This high carbon austenite is not stable indefinitely. At the higher austempering temperature and with sufficient time, carbide precipitation within

austenite occurs and austenite will eventually decompose to ferrite and carbide. Thus:

Reaction I : Austenite decomposing to bainitic ferrite and carbon
reached austenite $\gamma \rightarrow \alpha + \gamma_{hc}$

Reaction II: Further austenite decomposition to ferrite and carbide
 $\gamma_{hc} \rightarrow \alpha + \text{carbide}$.

The high toughness attributed to these irons stems from unique bainitic ferrite-austenite structure produced by first reaction, while the second reaction is undesirable as it reduces ductility and toughness.

The length of time at the austempering temperature can be quite critical when austempering ductile iron. Quenching from austempering temperature too early produces martensite as a result of incomplete stabilization of remaining austenite through carbon enrichment. When held too long the second stage of austenite decomposition can occur (carbide precipitation). The alloying elements Cu, Ni, Mo is effective in making the austempering time less critical.

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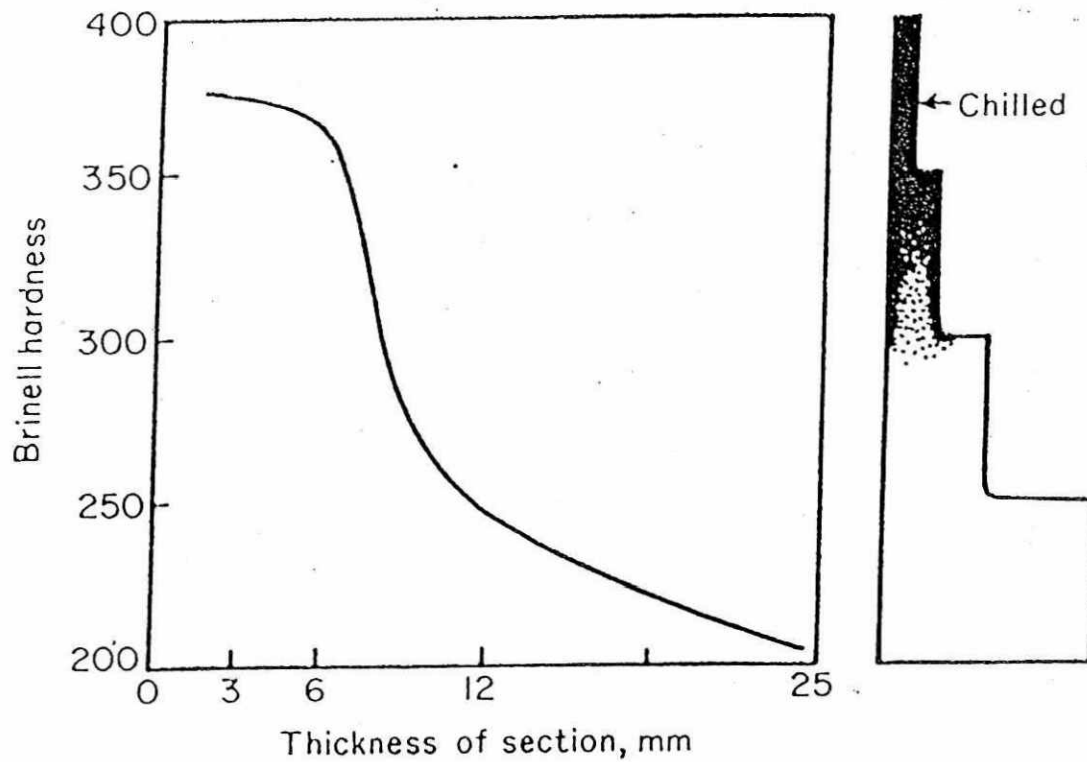


FIG. 1 The relation between the rate of cooling and hardness as indicated by sections of varying thickness

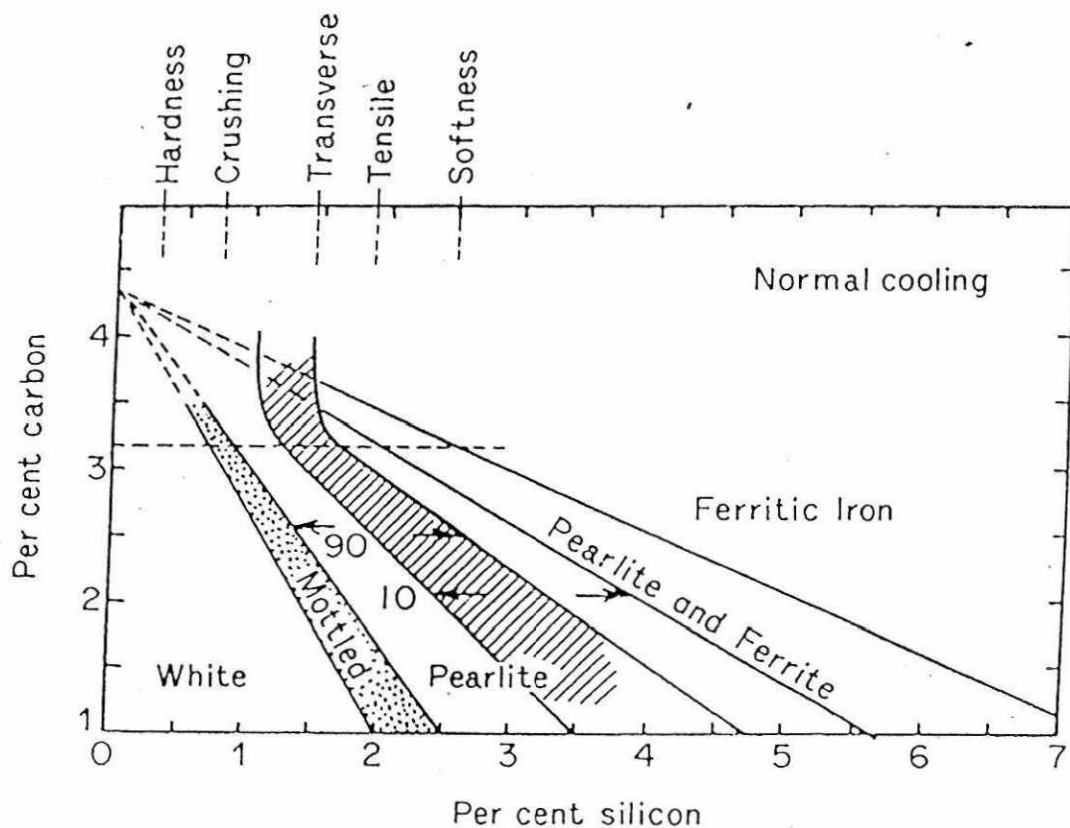


FIG. 2 Diagram indicating the structures of iron resulting from variation of silicon and carbon contents (Maurer)

Shaded area shows compositions common to 10 mm and 90 mm sections

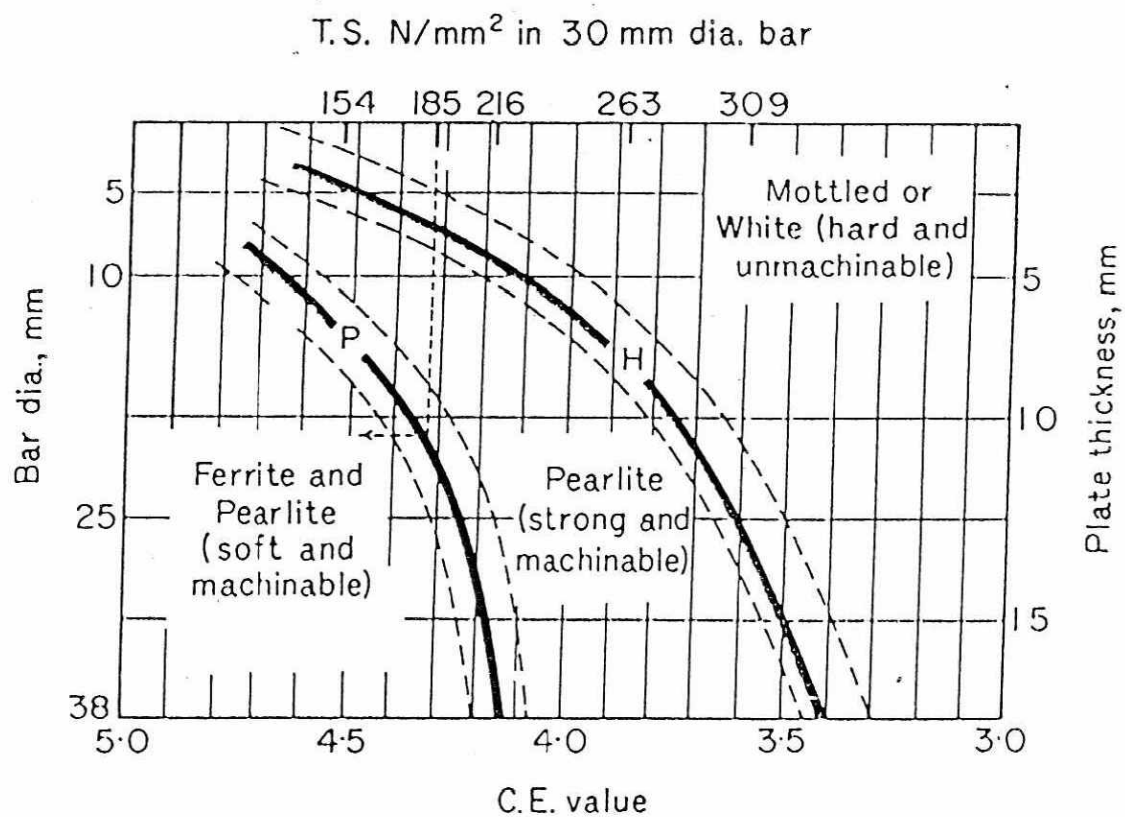


FIG. 3 Diagram relating section size, C.E. value, tensile strength and structure
(After BCIRA)

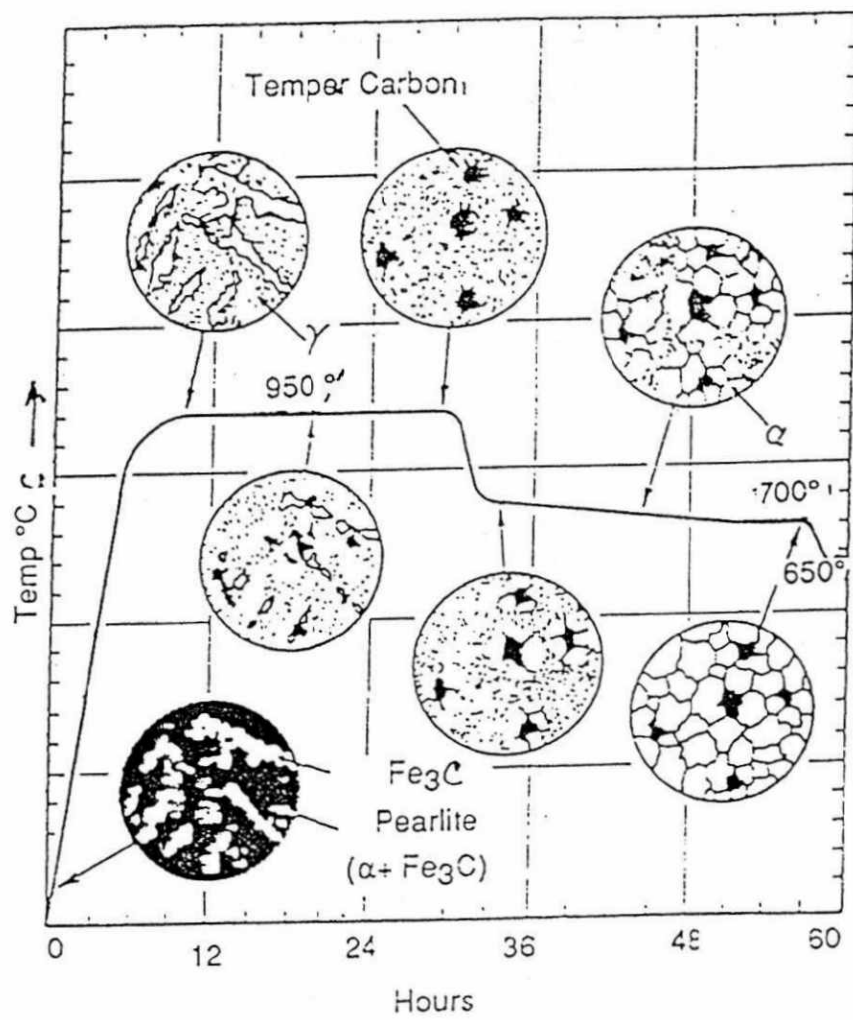
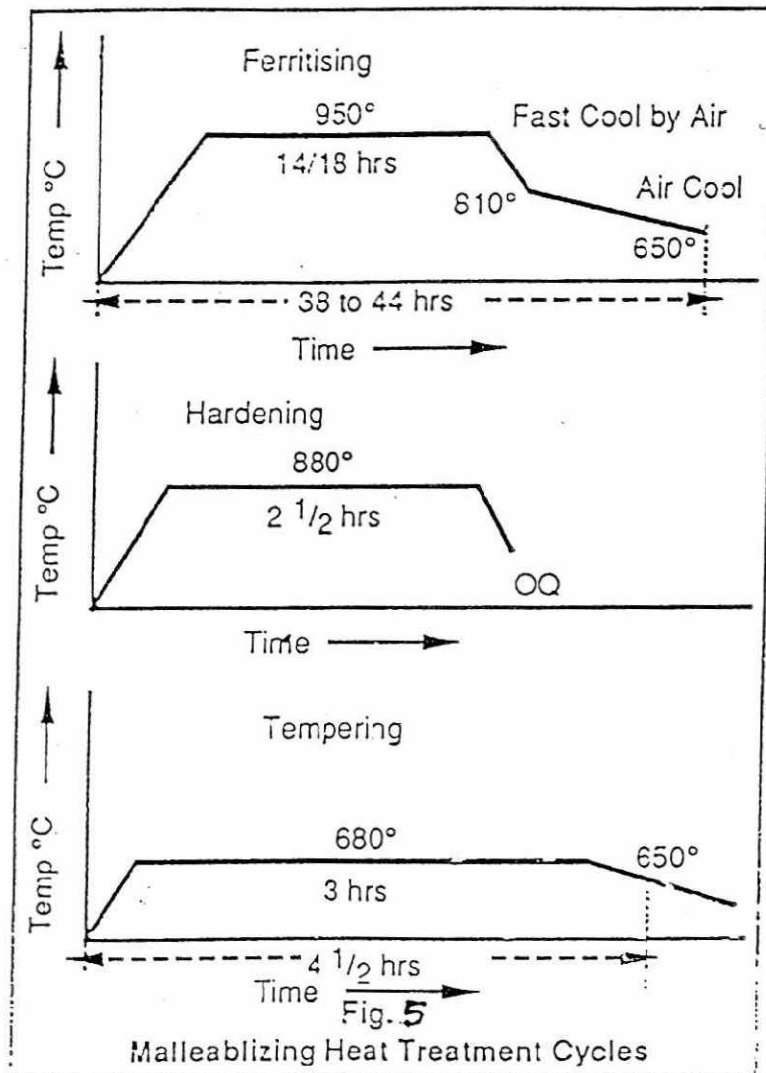


Fig. 4
Malleablizing Cycle



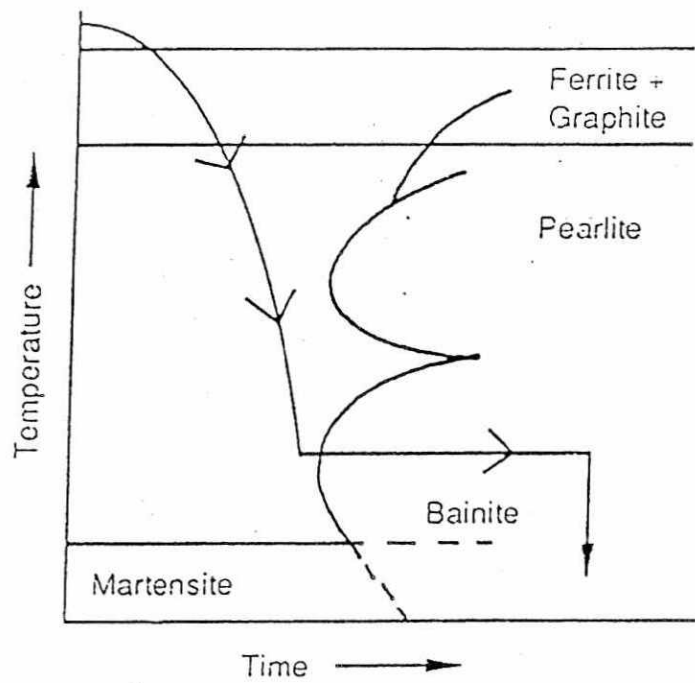


Fig 6
Schematic Representation of
Austempering Treatment

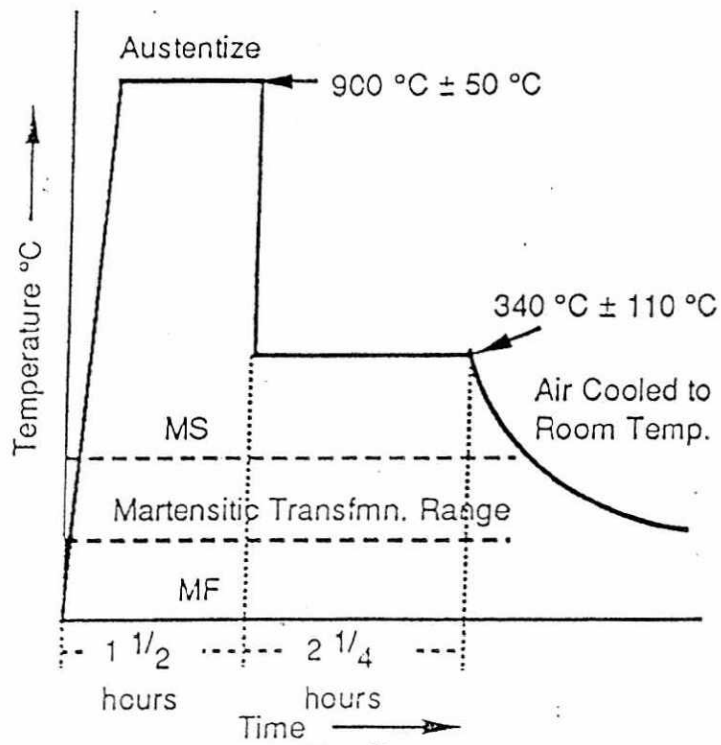


Fig 7
Schematic Representation of
Austempering Cycle