

MICRO-STRUCTURAL CHARACTERISTICS OF CAST IRONS

Sukomal Ghosh

Scientist

*National Metallurgical Laboratory
Jamshedpur - 831 007*

Whenever a cast metal is selected for specific application, first choice always goes to cast-irons in view of cost consideration. Cast irons are the least expensive to cast into shapes. Alternative is chosen only when the mechanical or physical properties of cast irons are found inadequate. Cast irons are essentially pig iron, remelted with addition of cast iron scrap, steel scrap and ferro-alloys to modify the composition to the final specification. The major constituents of cast irons are thus, carbon, silicon, manganese, phosphorus and sulphur. In cast iron, the carbon content is usually in excess of the maximum solubility limit of carbon in iron. The carbon ranges from 2 to 4%. In cast irons, carbon is present in two forms. A stable form shows presence of carbon as free graphite and an unstable form indicates presence of carbon in a combined form. The family of cast irons are classified depending on the form of carbon present.

Grey cast irons are characterised by the presence of all or most of the carbon in the form of free 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 border line composition which solidifies partly as a white iron and partly as a grey iron under prevailing conditions of cooling is termed as mottled iron. The other types of cast irons are also widely accepted as separate class owing to their properties. The malleable cast iron, which is produced by heat treating (malleablizing) a white iron casting, undergoes permanent deformation before its fracture and thus, derives its name. The spheroidal graphite (SG) iron or ductile iron exhibits a high strength coupled with ductility. The graphites are essentially free graphite in the form of spheroid. Alloyed cast-irons are also belonging to the family of cast irons which are produced in a lesser volume for specific applications, alloying a grey, ductile, or white iron base. In the family of cast iron, in terms of production and application, the grey iron occupies the privilege position.

The various types of grey iron are most commonly designated by a class number which indicates their minimum tensile strength requirement. For example, a class 30 requires a minimum tensile strength of 30 kilopounds per square inch. Many applications, however, requires criterion other than choice of grade only. Moreover the engineering properties do not all increase with the class number. For example, the components requiring resistance to heat checking viz. clutch plates, brake drums, are made of lower grades. In heat shock applications such as ingots, a higher grade iron would fail early in comparison to lower grade of grey iron. The components experiencing vibration preferentially cast with lower tensile irons which possess

better damping capacity. The general directions of increase in several properties with grey iron classes are indicated in the Table-1.

Table-1 : General direction of increase in various properties of grey iron

Grey class	20	30	40	50	60
		All strength			
	<-----	Machinability			
	<-----	Heat shock resistance			
		High temperature strength			
	<-----	Damping capacity			
		Modulus of elasticity			
	<-----	Producibility			
		Wear resistance			
	<-----	Thinner section possible			

Structure - Property Correlation

Structurally the matrices of grey cast irons contain varying proportion of ferrite and pearlite. Grains of essentially carbon-free iron as they appear under microscope are termed as ferrite. In comparison to 'ferrite' constituents of a plain-carbon steel, the cast iron 'ferrite' is relatively harder, as it contains some manganese and appreciable amount of silicon in solid-solution. Pearlite, under microscope, is identified as an alternate layers of soft ferrite and hard iron carbide (cementite). This lamellar structure with alternate soft and hard layers is very strong and tough. Hardness, strength, machinability and wear-resistance of pearlite varies with the fineness of its lamellae* are not resolved by an optical microscope at 500X magnification. In grey cast irons, over and above of these matrices, a relatively large amount of (3% by weight, 12% by volume) soft, brittle graphite flakes are also present which disrupt the continuity of the plastic matrix. The edges of the graphite flakes are usually sharp and each acts as an internal notch which initiates a crack in the plastic matrix upon deformation. The grey-iron thus becomes brittle. On the other hand, because of the fact that the internal structural discontinuities offer sites for the local dissipation of vibrational energy; the grey-irons exhibit a good damping capacity (Fig.1.) The structure of grey iron permits the vibrations to be absorbed internally and finds application as a base for machinery or any equipment subject to vibration. Because of the discontinuities offered by graphite and lubricity of graphite, grey irons are superior to steel in respect of machinability. The high silicon content of the grey-irons, in comparison to mild steel, classifies it as a better atmospheric and other corrosion resistant material. The notch insensitiveness property of grey iron also helps in its wider application. The influence of an external notch is not felt appreciably in reducing in strength of a grey iron as it inherits so many internal notches from the edges of graphite flakes.

*The strongest shows a hardness of 300 BHN and be so fine that the lamellae

A white -iron is identified by its massive primary carbide. The 'primary' carbides are those, which form during solidification directly from liquid iron and not during subsequent cooling of casting or heat treatment. Unless the carbides are stabilized by alloys, they can be dissociated by a high temperature annealing. Massive carbides reduce machinability.

A malleable iron casting structure shows the temper carbon nodules or compacted aggregate form of graphite in a ferritic matrix. The structure shows a high strength and elongation. The production is however accomplished in two stages; first one involves production of white iron castings and second stage involves high temperature annealing of these castings. The malleable iron exhibits considerable higher mechanical properties compared to grey iron.

The spheroidal graphite (SG) iron in its as cast microstructure contains varying proportions of ferrite and pearlite in the matrix with distributed graphite nodules. These nodules do not influence the properties of the iron as flakes do. The properties of nodular iron therefore closely follow the properties of matrix.

The malleable cast iron as well as spheroidal graphite iron possesses some of the inherent qualities of grey-iron such as machinability, corrosion resistance and wear resistance properties. In respect of strength and ductility, both these irons are much superior compared to grey irons. These irons are, however, susceptible to external or surface notch embrittlement lacking the internal notches of flakes.

The factors which influence structure

The factors which influence the character of carbon in cast iron and subsequently the microstructure are :

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

The microstructure may also be altered by

- d) Alloying elements, and
 - e) Heat treatment
- (a) A high cooling rate tends to prevent the formation of graphite, promoting chilling. Fig.2 shows a relationship between the rate of cooling and hardness in a varying section thickness. The general solidification behaviour of iron-carbon alloys is shown in Fig.3. Below 210°C (1670°F), pure iron exists in the 'ferrite' form, which can dissolve only about 0.025% carbon. At temperatures between 910°C (1670°F) and 1393°C (2540°F), pure iron assumes a form which can dissolve upto 2% carbon, and this form is termed as austenite. The phases and micro-constituents in slowly cooled Fe-C alloys are listed in Table-2. When the solubility of iron for carbon is exceeded, the carbon precipitates in one of the two forms, either as metastable Fe₃C compound (cementite), or as

free graphite. Normally cementite precipitates at compositions less than about 2% carbon. Above 2% carbon, either cementite or graphite may precipitate depending on the cooling rate and compositions of the melt. If an iron alloy exceeds about 2% carbon, carbon does not have to nucleate from the decomposition of the austenite, it can form directly from the melt by a eutectic reaction. Cementite (Fe_3C), can still nucleate at the eutectic more rapidly than graphite, but on sufficiently slow cooling, graphite itself is able to form and grow. The effect of cooling rate on the microstructure of an alloy of about 8% carbon is shown in Fig.4. 'At a very slow rate' of cooling, the phase changes in such alloy will be similar to that of 'slowly cooled', except that at the eutectoid (op), cooling will be sufficiently slow to permit graphite to precipitate rather than pearlite.

- (b) The grey iron is usually analysed for C, Si, S, P, Mn as constituents. The carbon lowers the melting point of the metal, imparts fluidity and produces more graphite. The general structural effects of some elements in cast irons are listed in Table-3.
- (c) Presence of graphite nuclei at the time of solidification promote solidification directly as graphite. Superheating destroy these graphitic nuclei and induce greater under cooling. Since $\gamma\text{-Fe}_3\text{C}$ eutectic temperature is at few degrees below the γ -graphite eutectic (Fig.3), 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.
- (d) The alloyed cast irons are considered as a separate class. The alloy content in them exceeds three percent and they can not be produced by ladle additions to irons of otherwise standard compositions. Thus nickel-alloyed irons (Ni-resist) finds application in corrosive and elevated temperature services, high chromium white irons are used for wear and heat resistance application, nickel-chromium white irons (Ni-hard) and molybdenum-chromium white irons are used for wear and abrasion resistance applications.

Irons containing 1 or 2% nickel are grey and machinable, the combined carbon being present in a matrix of fine grained pearlite. On increasing nickel beyond 2% or so, other irons become gradually harder, the pearlitic matrix transforms into sorbite (fine-pearlite). The hardness continues to increase, reaching a maximum with 5-8% nickel, when the matrix become martensite. Further increase in the nickel content over 8% leads to a gradual reduction in hardness, owing to replacement of martensite by austenite. Irons with more than 20% nickel contain only austenite.

These various alterations in structure are shown in Fig.5. The nickel cast irons thus are divided into three classes :

- (i) Within pearlite range; containing upto 2% Ni,
- (ii) Hard cast irons, e.g. Ni-hard containing 5-7% Ni, and
- (iii) Austenitic irons e.g. Ni-resist.

The chromium when alloyed in cast irons increases the proportion of combined carbon. Increased strength and hardness are thus achieved. In wear resistance application, chromium is added in conjunction with nickel, the combination produces irons superior to those resulting from the use of either constituent separately. The chromium offsets the graphitising tendency of nickel, and the nickel corrects the chilling effect of chromium. In general, nickel chromium irons have both graphite inclusions and a matrix of refined character, being thus hard and strong, and resistant to wear.

- (e) Heat treatment causes certain structural changes in the object responding to subsequent improvements in the properties in respect of mechanical properties, machinability, homogeneity, relieving of stresses, hardening and others.

In general, any cast iron, i.e. grey, malleable or spheroidal graphite type when heated above the A_1 temperature (Fig.3) form austenite with carbon content approaching 1.0% and there is no noticeable change in the prior graphite structure. The eutectoidal austenite forms more easily and quickly when the initial cast iron structure contains more pearlite rather than ferrite. Subsequent cooling from the austenitising temperature, and mode of cooling - such as, furnace cooling (annealing), air cooling (normalising), cooling in oil or water (quenching) lead to modification of matrix structure as required. Thus, a range of matrix structures from soft to very hard can be produced by heat-treatment.

However, amongst the family of cast iron, the malleable iron and austempered ductile iron are distinguished as heat treated product of basic structure of white iron and ductile iron respectively.

The most common malleabilizing treatment is a two stage process. In the first stage, the castings (white iron) are heated to 900-950°C (1650-1750°F). At this temperature the massive carbides dissolve and 'temper carbon' nodules precipitate. Castings are held at temperature until the structure consists of austenite and temper carbon. They are then furnace cooled as rapidly as convenient to about 760°C (1400°F). The second stage of the anneal consists of slowly cooling through the critical region, 700 to 760°C (1300-1400°F). The slow cooling through the critical range dissolves any pearlite that may precipitate and reprecipitate it on the already existing graphite nodules. The metallurgical structures obtained at various stages of annealing cycle are shown in Fig.6.

The austempered ductile irons are heat treated product of alloyed ductile 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 castings are heated to suitable austenitising 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 there for the time required for transformation to occur. The desired matrix structure of austempered ductile iron consists of a two phase mixture of acicular (or bainitic) ferrite and austenite. During austempering, bainitic ferrite 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 :

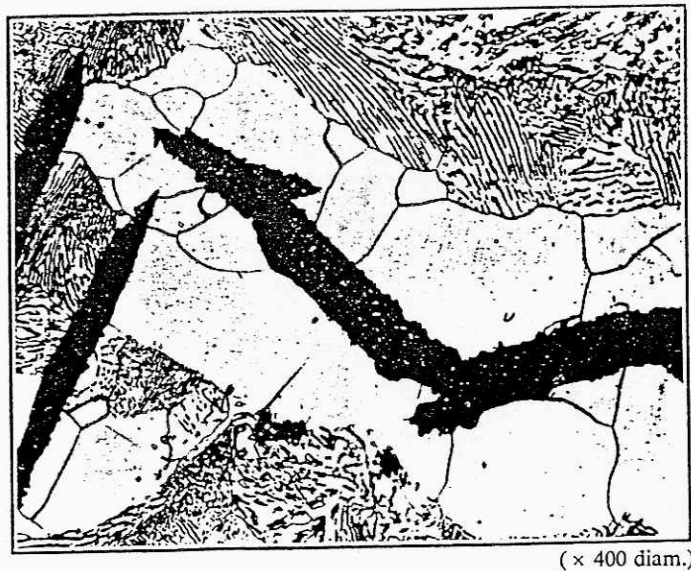
Reaction-I : Austenite decomposing to bainitic ferrite
and carbon rich austenite; $\gamma - \alpha_b + \gamma_{hc}$

Reaction - II: Further austenite decomposition to ferrite ,
and carbide; $\gamma_{hc} \rightarrow \alpha_b + \text{carbide}$

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. A schematic representation of austempering treatment and cycle is shown in Fig.7.

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(× 400 diam.)

Fig.A General grey iron structure (ferrite-pearlitic).

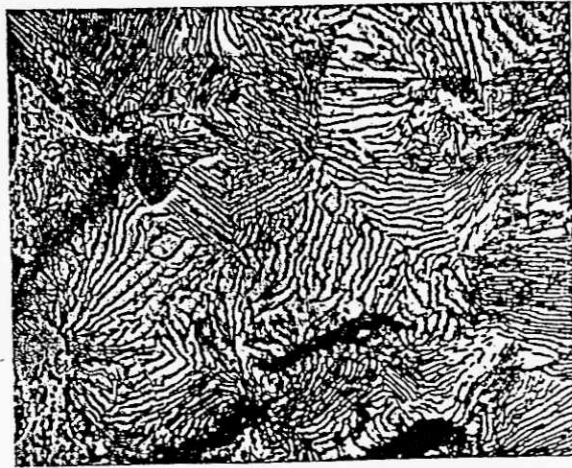


(a) From wall, $\frac{1}{8}$ in. thick



(b) From head, 7 in. in diameter

Fig.B Variation of graphite in different parts of a diesel compressor cylinder casting.



x 500

Fig.C Pearlitic grey iron.



(x 100 diam.)



(x 400 diam.)

Fig.D White iron.

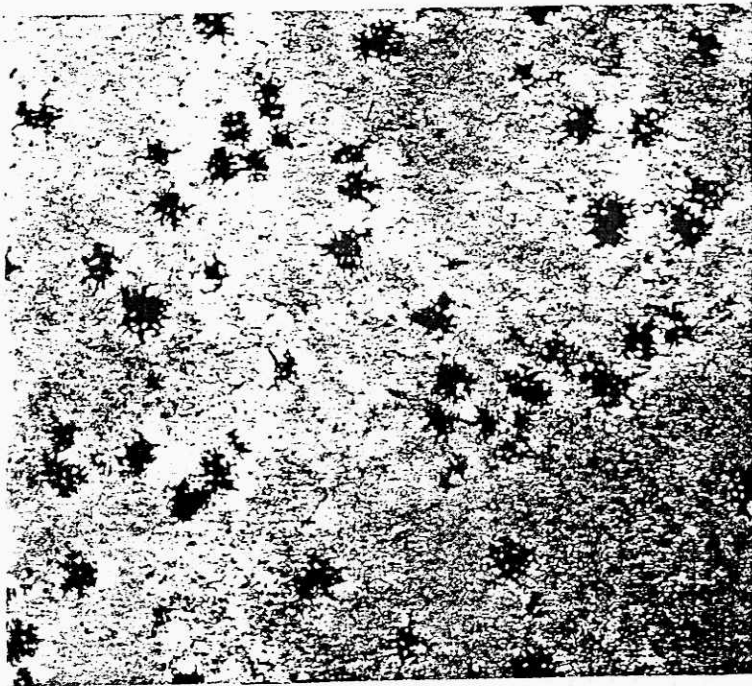
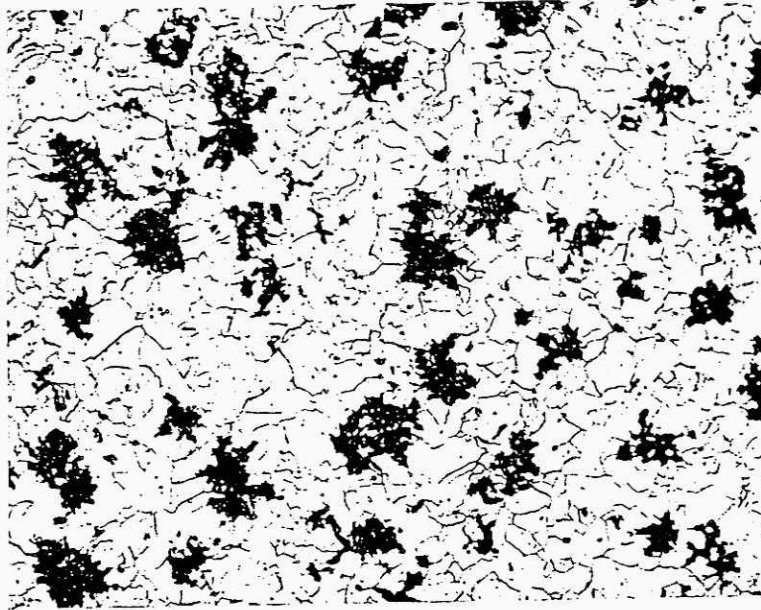


Fig.E Ferritic and Pearlitic Malleable iron.

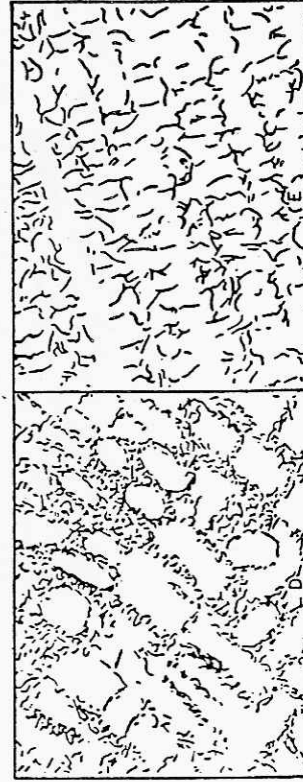
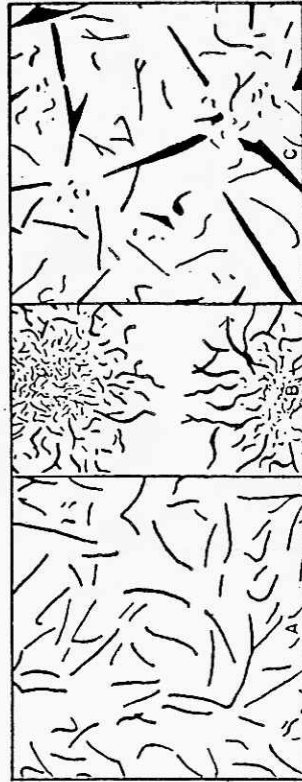
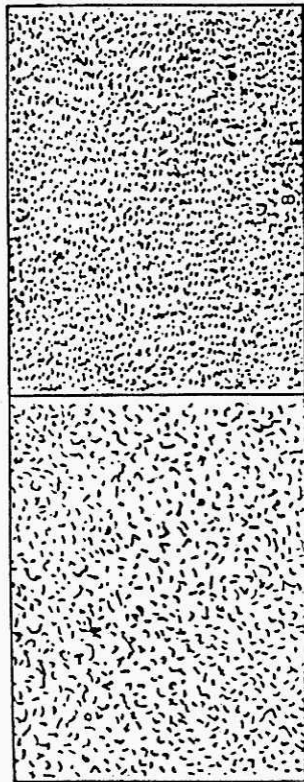
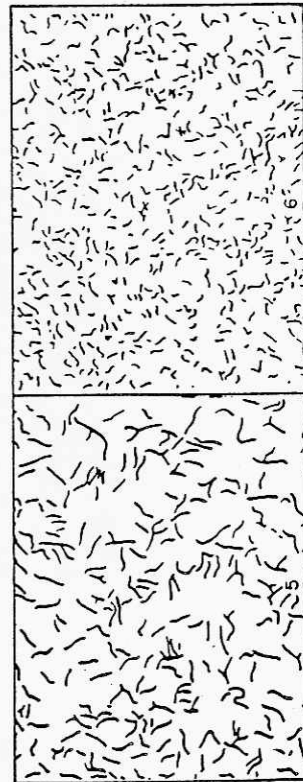
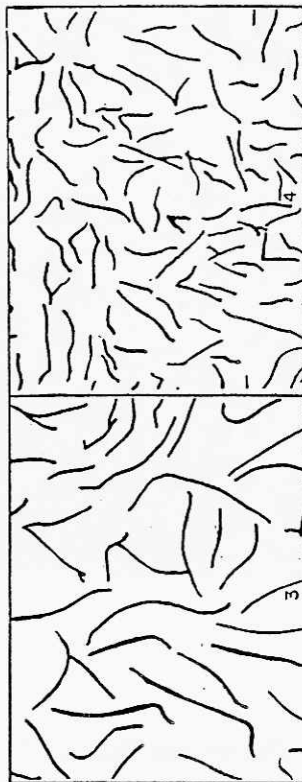
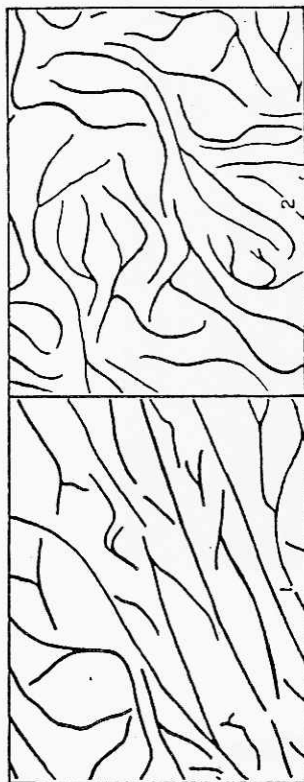


Fig.F AFS and ASTM graphite flake type and size rating charts $\times 100$

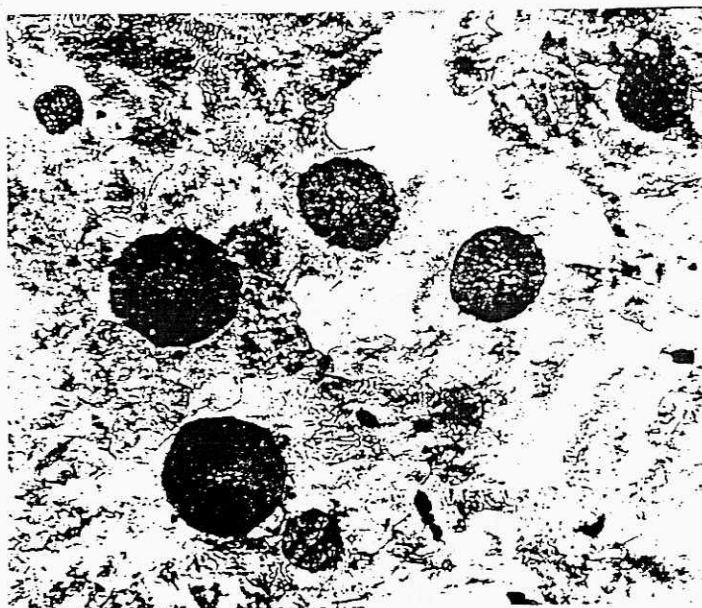
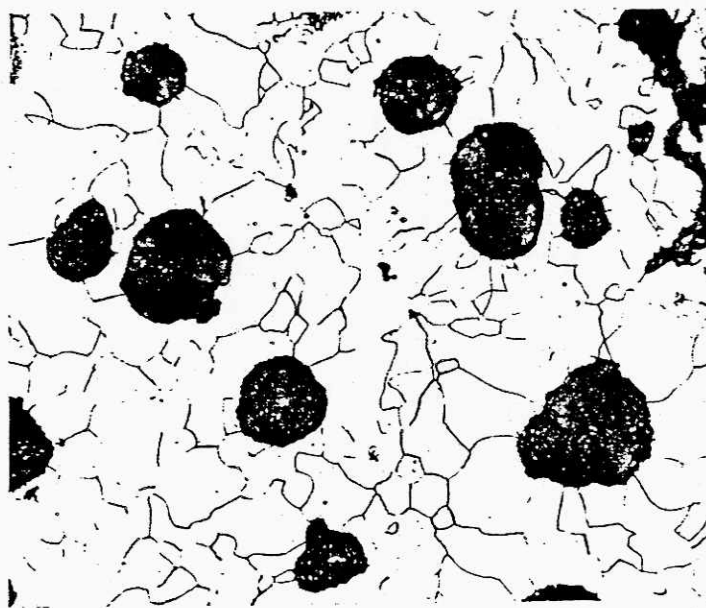


Fig.G As cast SG iron; ferritic and pearlitic.

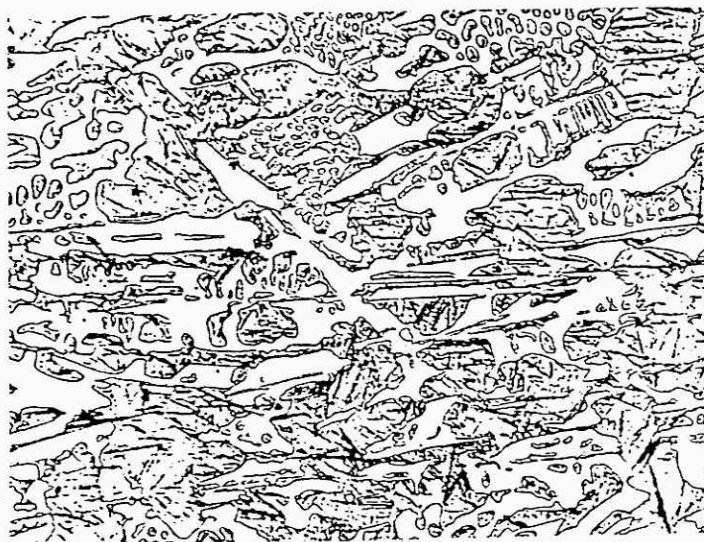


($\times 500$ diam.)



($\times 500$ diam.)

Fig.H (a) Pearlitic structure of cast iron containing 1% nickel.
(b) Martensitic structure of cast iron containing 5% nickel.



($\times 250$ diam.)



($\times 250$ diam.)

Fig.I (a) Ni-hard.
(b) Ni-resist.

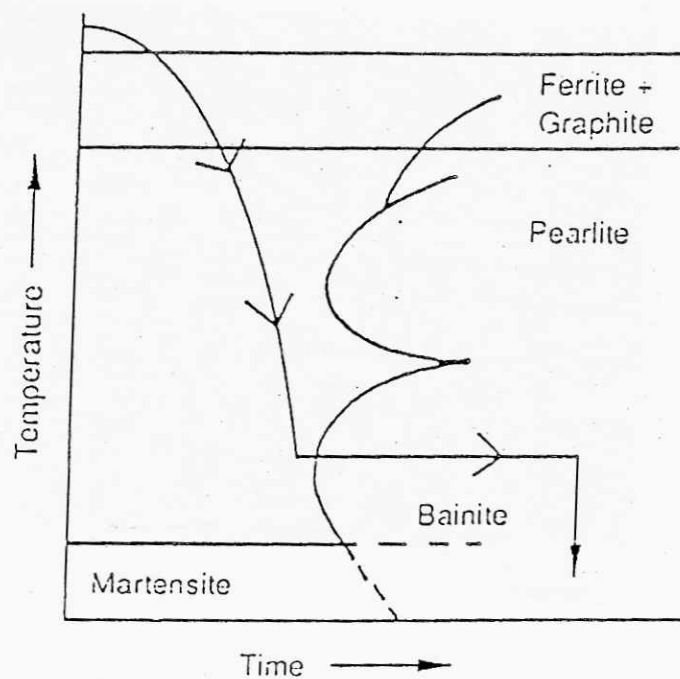


Fig
Schematic Representation of
Austempering Treatment

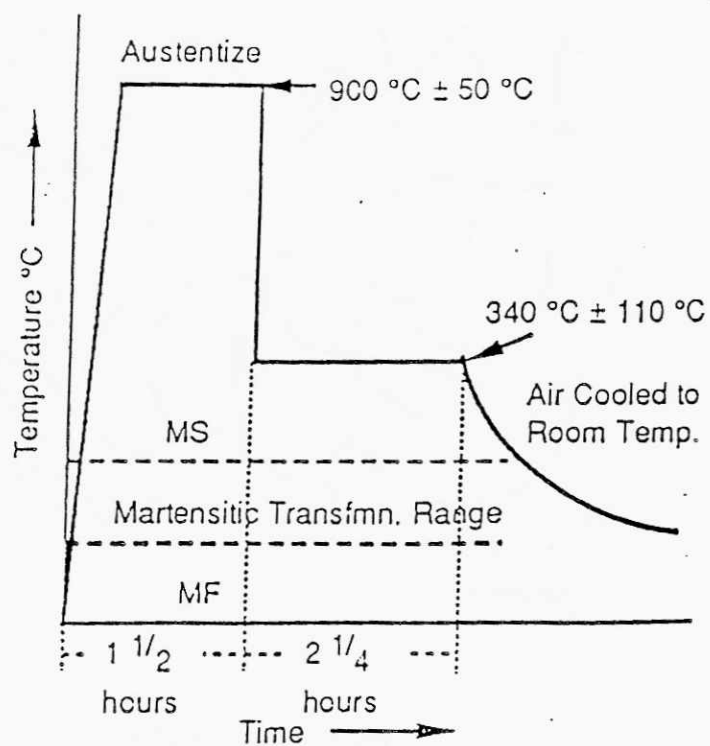


Fig
Schematic Representation of
Austempering Cycle

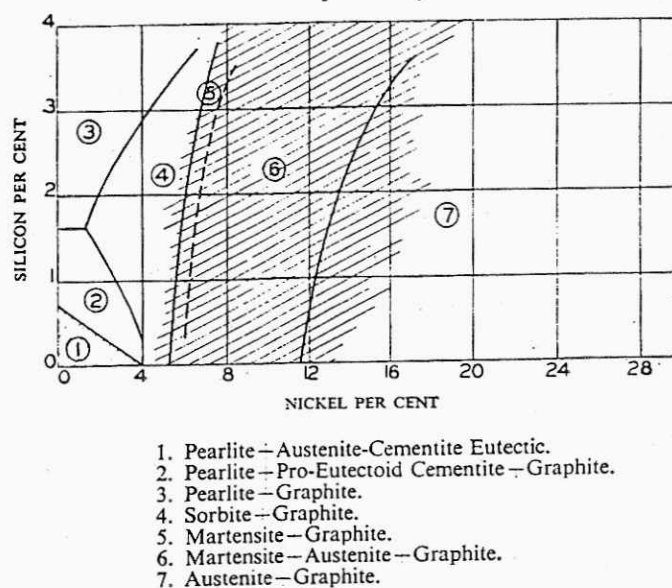


Fig.5 Constitution of Ni-Si-Fe alloys with 3.5% carbon. Shaded area indicate ranges of unmachinability.

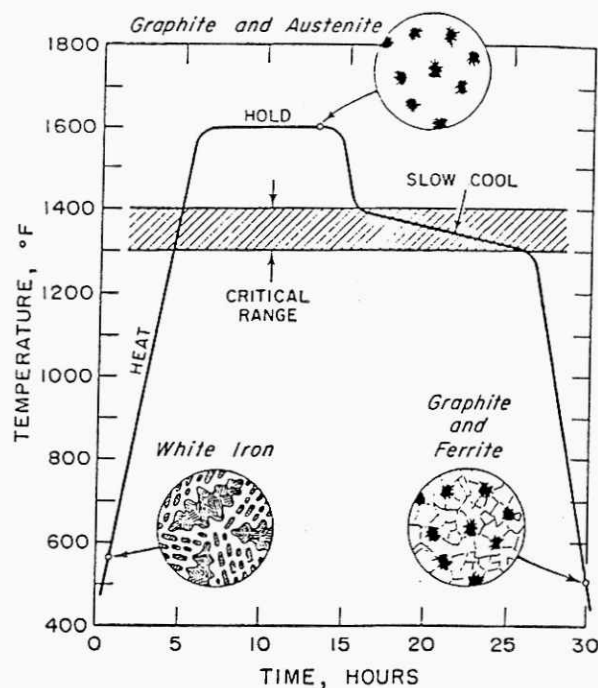


Fig.6 Typical annealing cycle for ferritic malleable iron.

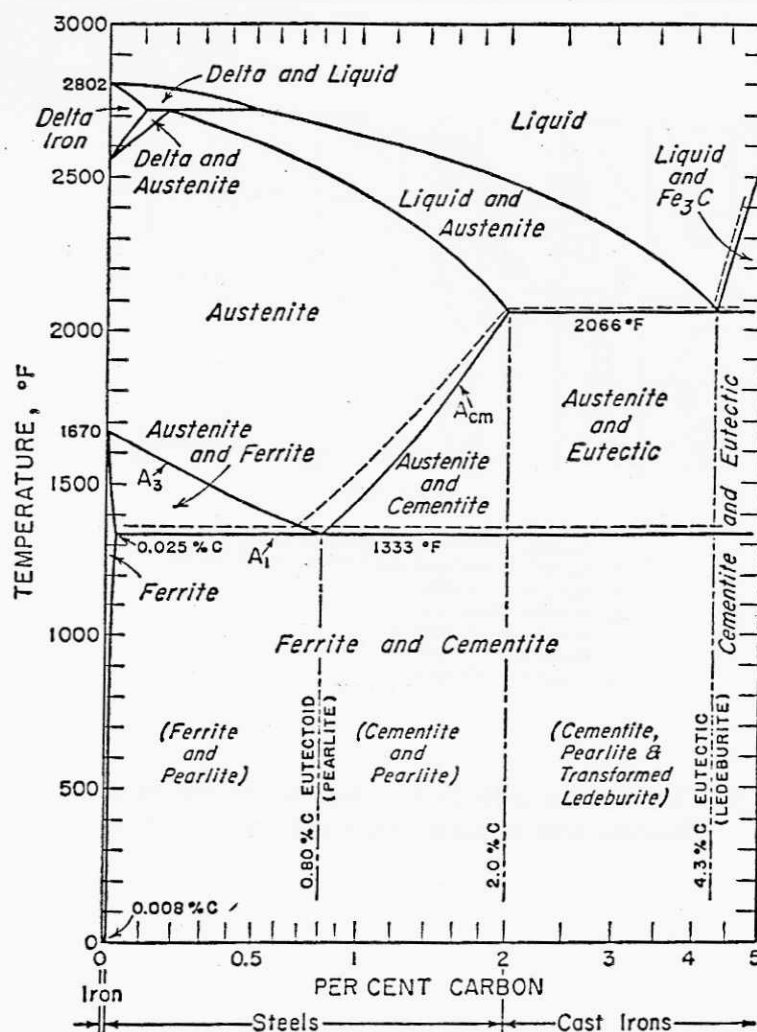


Fig.3 Iron-Ironcarbide phase diagramme. Iron-Irongraphite system shown by dashed line.

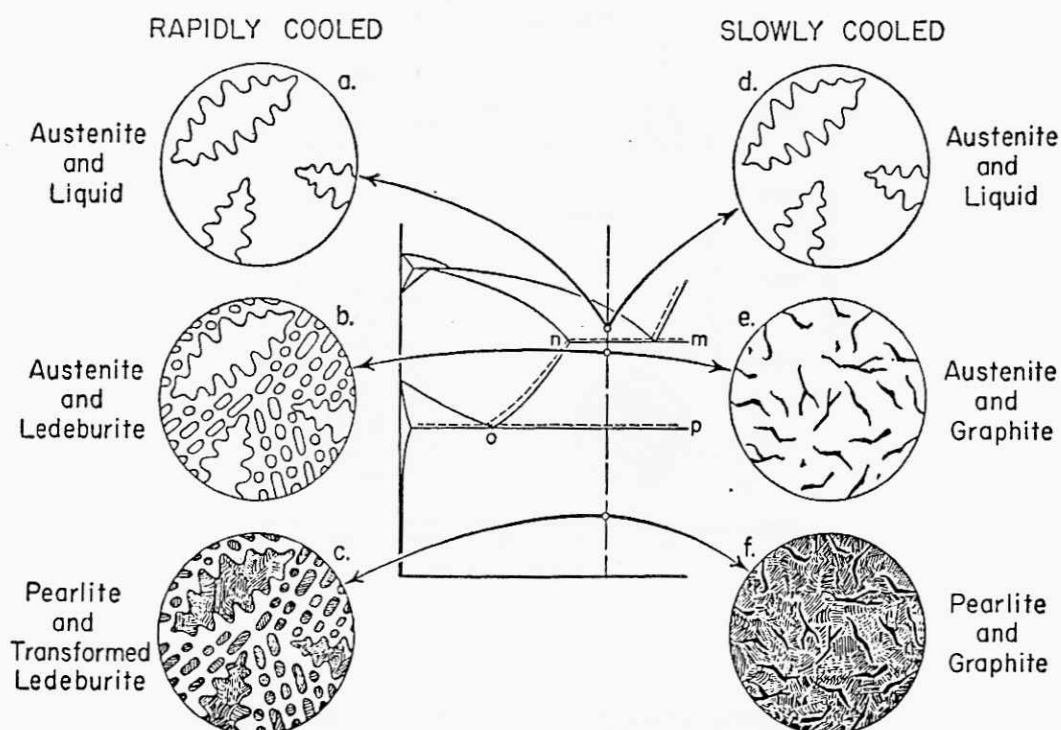


Fig.4 Microstructures obtained on solidification of cast irons

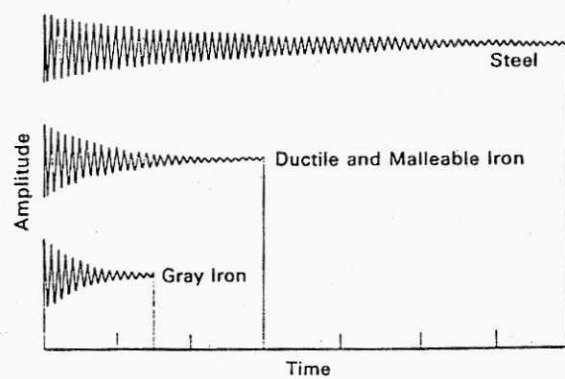


Fig.1 The relative ability of ferrous metals to quell vibration.

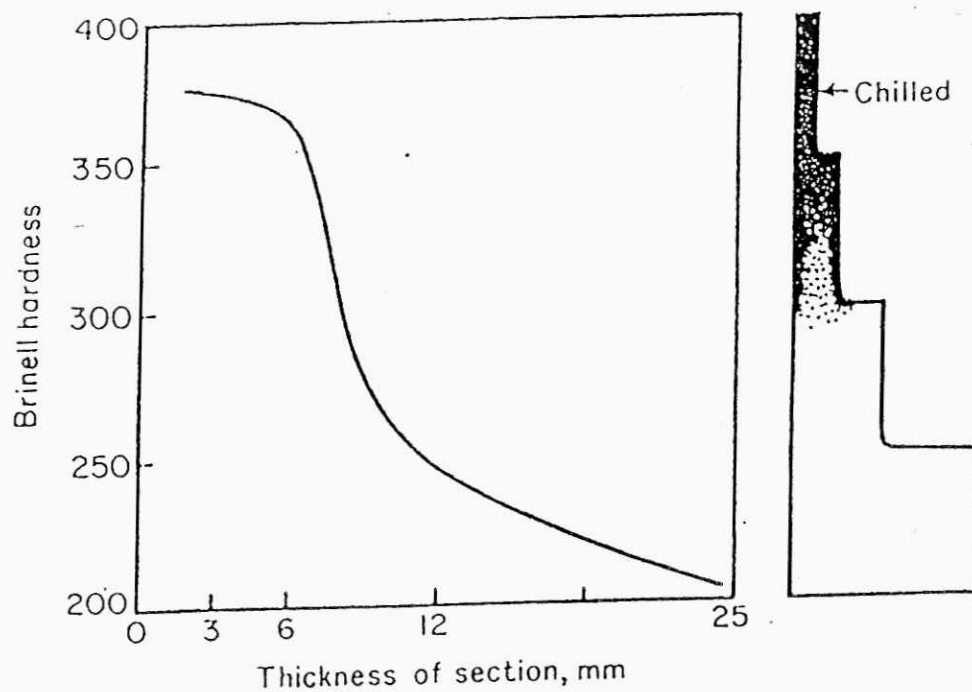


Fig.2 The relation between the rate of cooling and hardness as indicated by sections of varying thickness.

Phases and Micro-constituents in Slowly-cooled Iron-Carbon Alloys

Symbol or Formula	Phase	Micro-constituent
α	Alpha (Ferrite), a solid solution of carbon (0.025 per cent max.) in α -iron	Free ferrite
γ	Gamma (Austenite), a solid solution of carbon (2.0 per cent max.) in γ -iron	Not stable below about 700° C.
δ	Delta, a solid solution of carbon (0.51 per cent max.) in δ -iron	Not stable below 1400° C.
Fe_3C	Cementite (Iron carbide), a compound between iron and carbon of constant proportions	Free cementite
$\alpha - \text{Fe}_3\text{C}$	A two-phase mixture of ferrite and cementite of constant proportions	Pearlite (a mechanical mixture, resolvable at high magnification)

Table 2

Structural Effects of Some Elements in Cast Irons

Element	Effect During Solidification	Effect During Eutectoid Reaction
Aluminum	Strong graphitizer	Promotes ferrite and graphite formation
Antimony	Little effect in amounts used	Strong pearlite stabilizer
Bismuth	Carbide promoter, but not carbide former	Very mild pearlite stabilizer
Boron up to 0.15%	Strong graphitizer	Promotes graphite formation
Boron greater than 0.15%	Carbide stabilizer	Strong pearlite retainer
Chromium	Strong carbide former. Forms complex carbides which are very stable	Strong pearlite former
Copper	Mild graphitizer	Promotes pearlite formation
Manganese	Mild carbide former	Pearlite former
Molybdenum	Mild carbide former	Strong pearlite former
Nickel	Graphitizer	Mild pearlite promoter
Silicon	Strong graphitizer	Promotes ferrite and graphite formation
Tellurium	Very strong carbide promoter, but not stabilizer	Very mild pearlite stabilizer
Tin	Little effect with amount used	Strong pearlite retainer
Titanium under 0.25%	Graphitizer	Promotes graphite formation
Vanadium	Strong carbide former	Strong pearlite former

Table 3