HEAT TREATMENT OF FORGINGS

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INTRODUCTION

Ferrous materials are widely used for the manufacture of components for the engineering applications. This is because of the fact that these materials can have wide range of mechanical properties. According to requirements one can select a particular grade of iron and steel and by suitable processes shapes can be given and then by heat treatment the required physical properties can be imparted. Application and use of steel is much more wide than that of iron is well known, because of its improved characteristic as regards hot and cold deformation.

A steel is usually defined as an alloy of iron and carbon with carbon content between a few hundreth of a percent upto about 2% by weight. Other alloying elements can amount to 5.0% by weight in low alloy steels and in high alloy steels more than 10% by weight such as tool steels and stainless steels etc. Steels can exhibit a wide variety of properties depending upon composition as well as phases and micro-constituents present, which in turn depend on mechanical work during deformation, such as forging, rolling and final heat-treatment.

The table indicates the improvement in physical properties as a result of heat treatment of a plain carbon steel having carbon content of 0.35% and Manganese content of 0.70%.

Physical properties	As Forged	As Heat treatment
Tensile strength (Tons/Sq.in.)	37.0	43.0
Yield strength (Tons/Sq.in.)	20.0	27.0
% Elongation	23.0	27.0
Charpy 'V' notch impact (Joules)	14.0	54.0
Hardness (BHN)	165	190

BASIC OF HEAT TREATMENT

Heat-treatment is an operation involving the heating of the solid metal to a definite temperature and to allow solid solution of different phases and chemical compounds at that temperature, followed by cooling at suitable rates in order to obtain certain physical properties which are associated with changes in the nature, form, size and distribution of microconstituents.

To understand the above statement one should know the structure of 'plain steels' and 'allotrophy of iron'

The essential difference between ordinary steel and pure iron is the amount of carbon in the former, which reduces the ductility, but increases the strength and the susceptibility to hardening when rapidly cooled from elevated temperature. On account of various microstructures which may be obtained by different heat treatments. The appearance of structure of pure iron is typical, it is built up of a number of crystals of the same composition given the name 'Ferrite' and is very soft. The addition of carbon to the pure iron results in a considerable difference in the structure which now consists of two constituents one is pure iron i.e. "Ferrite' appears as white under microscope and the dark parts representing the constituents containing the carbon. The carbon is present as a compound of iron and carbon (6.67%) called "Cementite", Fe_3C. This is a hard and brittle constituent.

On microexamination these dark parts will be seen to consist of two components occurring as wavy or parallel plates alternately dark and light. The two phases are ferrite and cementite which form a eutectoid mixture containing 0.87% carbon and known as 'Pearlite". The highest strength is obtained when the structure consists only pearlite. The presence of free cementite masses increases the hardness but reduces the strength.

Fig-1 - is showing mechanical properties vs microconstituents dependent on % carbon content in plain carbon steels

Iron-Carbon Phase Diagram

The diagram which depicts the temperature at which phase changes occur during very slow cooling or heating, and in relation to the carbon content, is called the iron-carbon phase diagram. This diagram is the basis for a correct understanding of all heat-treatment operations, (Fig.2).

Carbon is an element that stabilizes austenite by increasing the range of austenite formation of steel. The maximum solubility of carbon in austenite is about 2.06% at 1147°C. The percentage carbon capable of going into solution in ferrite increases from zero at 910°C to a maximum of 0.02% at 720°C. On further cooling at room temperature this decreases to 0.008%. As the carbon content increases the transformation of austenite into ferrite decreases. This reaches a minimum value of 0.8% carbon at 723°C which is called eutectoid composition. Steels are classified with reference to this composition. Those with less than 0.8% carbon are called hypoeutectoid steel and those with more are called hypereutectoid steels.

REASONS FOR HEAT-TREATMENT OF FORGINGS

Forgings are commonly associated with banded grain structure, as well as large grain size or mixed large and small grain size dependent on forging practice. Alloy steel forgings are subjected to a conditioning treatment before final heat-treatment to obtain best possible physical properties and to maximise the life cycle under severe service conditions.

Hypereutectoid alloy steels are associated with carbide network after hot working. Elimination of carbide network and thus producing a structure that is more susceptible to 100% spheroidisation, calls for a simple heat-treatment. The spheroidised structure provides improved machinability and more uniform response to hardening.

Alloy carburising steel forgings are usually subjected to high temperature normalising prior to carburising to minimise distortion and to improve machinability.

Considering the above mentioned reasons it is imperative that the forgings are subjected to heat-treatment prior to final machining. The forgings are subjected to either Annealing or Normalising or both depending on the grade of steel and the forging practice. In case of high alloy tool steels it is recommended that reduction in size should be done in multistages and should be annealed in between stages or reductions.

Annealing

Annealing is a generic term denoting a treatment that consists of heating to and holding at suitable temperature followed by cooling at an appropriate rate, primarily for softening of metallic materials. Generally, in plain carbon steels annealing produces a ferrite-pearlite microstructure. Steels may be annealed to facilitate cold working, or machining, to improve mechanical or electrical properties, or to promote dimensional stability.

The "Fe-C" binary phase diagram can be used to better understand annealing processes. Although no annealing process ever achieves true equilibrium conditions, it can closely parallel these conditions. In defining the various types of annealing, the transformation temperatures or critical temperatures are usually used. These temperatures can be calculated using the actual chemical composition of the steel. The following equations will give an approximate critical temperature for a hypoeutectoid steel:

$$AC_1(°C) = 723 - 20.7\,(\%Mn) - 16.9\,(\%Bi) + 29.1(\%Si) - 16.9(\%Cr)$$

Std. deviation = $\pm$ 11.5°C

$$AC_3(°C) = 910 - 203\,(\%C) - 15.2(\%Ni) + 44.7(\%Si) + 104(\%V) + 31.5(\%Mo)$$

Std. deviation = $\pm$ 16.7°C

"**Guidelines for annealing**"

The following seven rules may be used as guidelines for development of successful and efficient annealing schedules :

1. The more homogeneous the structure of the as austenitized steel the more completely lamellar will be the structure of the annealed steel. Conversely, the more heterogeneous the structure of the as austenitized steel, the more nearly spheroidal will be the annealed carbide structure.

2. The softest condition in the steel is usually developed by austenitizing at a temperature less than 55°C above A_1 and transforming at temperature less than 55°C below A_1.

3. Because very long time may be required for complete transformation at temperatures less than 55°C below A_1 allow most of the transformation to take place at the higher temperature, where a soft product formed, and finish the transformation at a lower temperature, when the time required for completion of transformation is short,.

4. After the steel has been austentized, cool to the transformation temperature as rapidly as feasible in order to minimise the total duration of the annealing operation.

5. After the steel has been completely transformed, at a temperature that produces the desired microstructure and hardness, cool to room temperature as rapidly as feasible to decrease further the total time of annealing.

6. To ensure a minimum of lamellar pearlite in the structure of annealed 0.70 to 0.90% C tool steels and other low alloy medium carbon steels, preheat for several hours at a temperature about 28°C below the lower critical temperature (A_1) before austentizing and transforming, as usual.

7. To obtain minimum hardness in annealed hypereutectoid alloy tool steels, heat at the austenitizing temperature for a long time (about 10 to 15 hrs.) then transform as usual.

These rules are applied most effectively when the critical temperatures and transformation characteristic of the steel have been established and when transformation by isothermal treatment is feasible.

"Different types of annealing are applied for different purposes" :

Full Annealing

It consists of austenitzation of the steel followed by slow cooling. For hypoeutectoid steel, it consists of austenitizing the steel at 10-30°C above the AC_3 line and holding it at this temperature for a desired length of time, followed by slow furnace cooling. This leads to the formation of a fine ground austenite structure. The subsequent slow cooling enables the austenite to decompose at low degree of supercooling so as to form pearlite and ferrite. In case of hypereutectoid steel heated above AC_1 to spheroidize the proeutectoid cementite. Therefore it is the general practice to use spheroidized annealing. In case of heating above Acm temperature and cooled slowly results in formation of proeutectoid cementite at the grain boundries. Retarded cooling facilities ferrite precipitation as a separate cluster. This might result in soft spots during hardening and render the steel brittle to forming and service stresses, Fig.3 is showing full annealing temperature.

Spheroidized Annealing

This is done by heating the steel just above or slightly below AC_1 temperature for a prolonged time, followed by a slow cooling in order to soften the steel as much as possible. It is adopted to spheroidize the carbides of lamellar pearlite or secondary cementite.

Commonly four methods are practiced for this treatment :

First Method - The steel is heated nearer to AC_1 temperature and held at that temperature for a long time for the formation of coarse globular cementite, the temperature should be as close to AC_1 as possible.

Second Method - The steel is heated slightly above AC_1 temperature and held for a prolonged time followed by slow cooling at a rate of 10 - 20°C per hour upto 550 - 600°C and then cool in still air.

Third Method - It is heating the steel slightly above AC_1 and holding for a predetermined time and then cooling to just below AC_1 temperature and holding for prolonged time and subsequently cooling to the room temperature.

Fourth Method - Spheroidizing is done by repeatedly heating and cooling just above and below AC_1 temperature. During heating above AC_1 temperature only the small sized grains of cementite will dissolve in the austenite, but there is insufficient time for the larger cementite grains to dissolve. In the subsequent cooling cycle, the molecules of cementite are deposited mainly on the cementite grains that are not dissolved in the austenite. Hence a coagulation process occurs. This method taken less time compared to previous methods but difficult to perform.

Isothermal Annealing

This is derived from the exact knowledge of temperature - time diagrams. This treatment consists of austenitizing the steel at the full annealing temperature and then cooling rapidly to appropriate temperature below Ar_1 by 50 - 60°C. This temperature is held for a predetermined time enabling the complete austenite decomposition to take place for producing a structure having optimum machinability. After the transformation is complete, the steel is cooled in a furnace, or air cooled or rapidly cooled.

Normalising

Overheated forgings and very large forgings are normalised to refine the grain structure, to improve machinability, to relieve internal stresses and to improve mechanical properties.

Normalising consists of heating the steel above the critical temperature AC_3 or Acm and holding at this temperature for a short time depending on the grade of steel to achieve homogenization of austenite, hypoeutectoid steels are heated to 30 - 40°C above the Ac_3 temperature and held at this temperature for 20 - 40 mins. depending on the chemistry. Exceeding the indicated temperature range might attribute to excessive austenite grain growth. Grain growth may occur due to higher holding time. After desirable holding the material cooled in air the resultant microstructure are composed of fine pearlite with ferrite in hypoeutectoid steels. The newly formed grain boundries do not correspond to the old ones. Hypereutectoid steels are heated to 30 - 40°C above Acm temperature with a short holding just sufficient to complete phase transformation and then cool in air. Here alongwith grain refinement, dissolution of carbide network do take place. Microstructure corresponds to fine grained pearlite with cementite. This is more suitable for spheroidization. Alloy carburising steels are usually normalized at higher temperatures than the carburising temperature to minimise distortion in carburizing and to improve machinability.

To refine the grains and to obtain required hardness normalising and tempering is a preferred treatment for forgings of low-alloy heat resistant steels. (C-0.45%, Cr-1.0%, Mo-0.5% and V-0.3%) AISI - 4137 & AISI 4140.

Multiple Normalising - This is done to obtain complete solution of all lower temperature constituents in austenite by the use of high initial normalising temperature (e.g. - 925°C) and to refine final pearlite grain size by the use of a second normalising treatment at a temperature closer to Ac_3 temp. (e.g. - 815°C) without destroying the beneficial effects of the initial normalising treatment. This is normally applied to carbon and low alloy steels of large dimensions where extremely high forging temperatures have been used (e.g. Loco axle forging) made of carbon steels. Forgings made of a low carbon steel (o.18%) with 1% Mn intended for low temperature service are double normalised to meet subzero impact requirements.

Mechanical properties of steels as a function of composition and structure

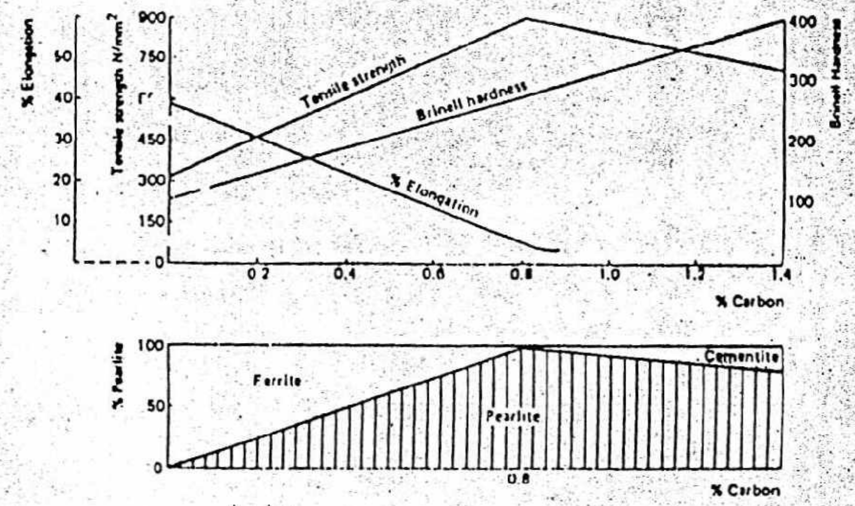


FIG:10

Pearlite →

(b)

(c)

↑ Bainite

FIG: 9

Martensite →

(d)

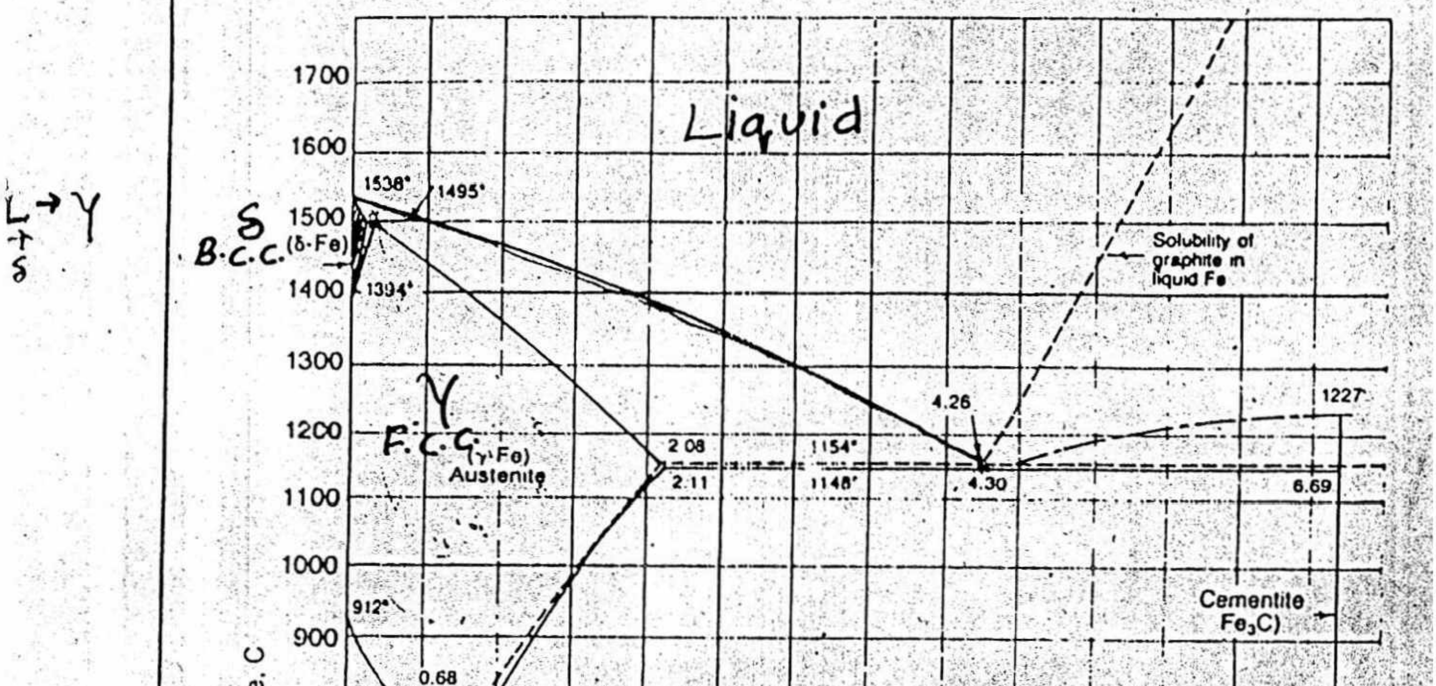


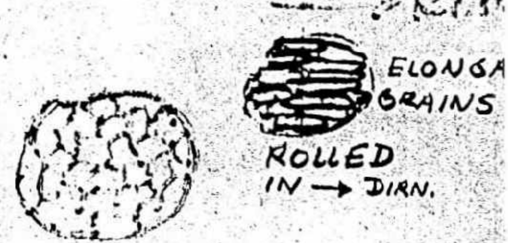
Fig. 2.0. The Fe-C equilibrium diagram up to 7% carbon. Solid lines indicate Fe-Fe_3C diagram; dashed lines indicate Fe-graphite diagram. ~~(... 1.12)~~

Steels: Low C <0.2%
Medium C <0.6%
High C <2%

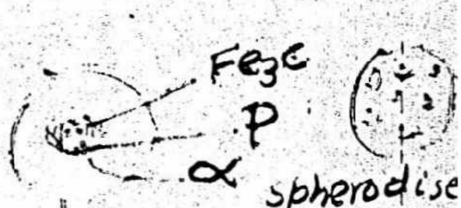
Cast Irons: Grey graphite + ferrite
White cementite + ferrite

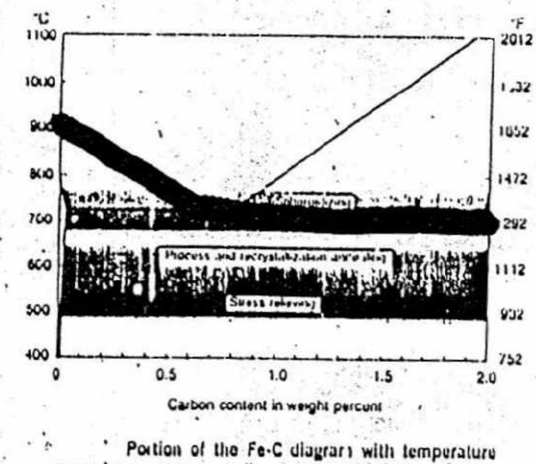
Figure 2.0 shows the Fe-C equilibrium diagram for carbon con
tents up to 7%. Steels are alloys of iron, carbon, and other element
that contain less than 2% carbon—most frequently 1% or less. Therefor

ANNEALING

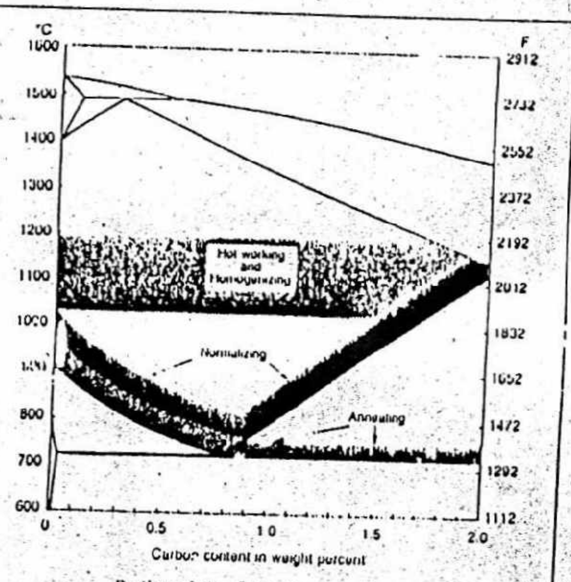


- [redacted] recrystallisation
  - removal of internal stresses
  - ductility, toughness
  - equiaxed ploygonal ferrite
  - no phase transformation
  - temp : below L.C.T. (A1) 450-700°C
- [redacted]:
  - heat above A3 - check grain coarsen
  - furnace / box cool
  - hyper eutectoid : coarse Pearlite cementite network
  - electrical sheets
- [redacted] hypereutectoid
  fine P + Cementite
- [redacted] : high carbon steels
  - globular carbide in ferrite : machine



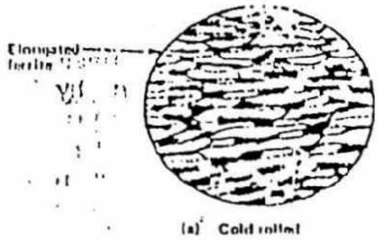


Portion of the Fe-C diagram with temperature ranges for process annealing, recrystallization annealing, stress relieving, and spheroidizing indicated. Courtesy of M.D. Geib, Colorado School of Mines, Golden

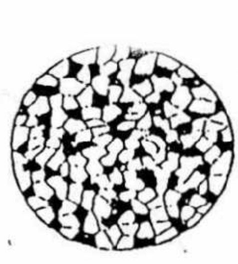


Portion of the Fe-C diagram with temperature ranges for full annealing, normalizing, hot working, and homogenizing indicated. Courtesy of M.D. Geib, Colorado School of Mines, Golden

Fig. 3.



(a) Cold rolled



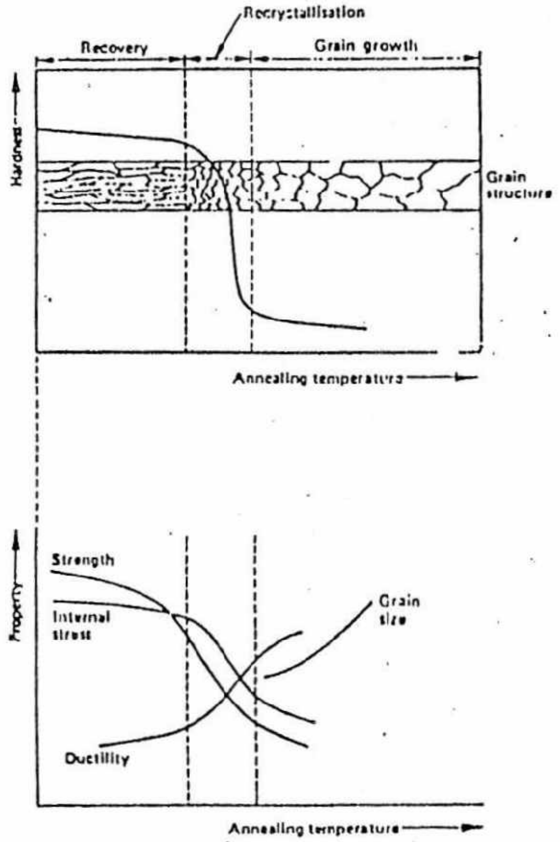
Normalised carbon steel

Fully annealed carbon steel

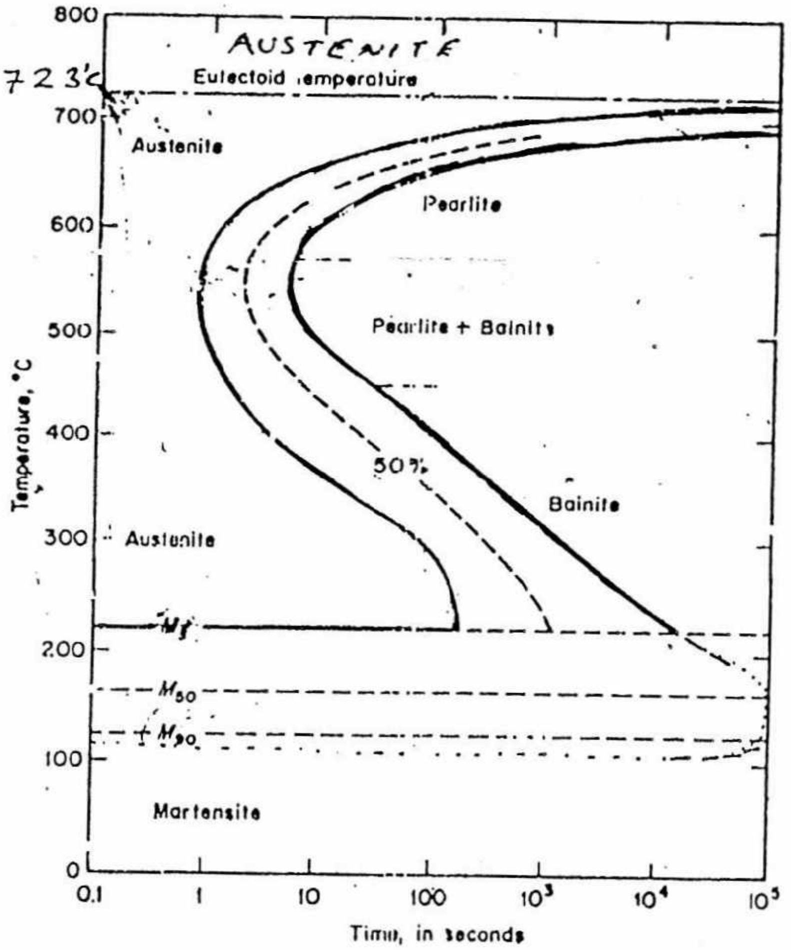
FIGS: 1 2 3

Effect of annealing temperature on properties of cold-worked metal

FIG. 4.



TIME TEMPERATURE TRANSFORMATION



0.8%C steel
TIME–TEMPERATURE–TRANSFORMATION

Austenite
γ
(F.C.C.)
> 723°C

→

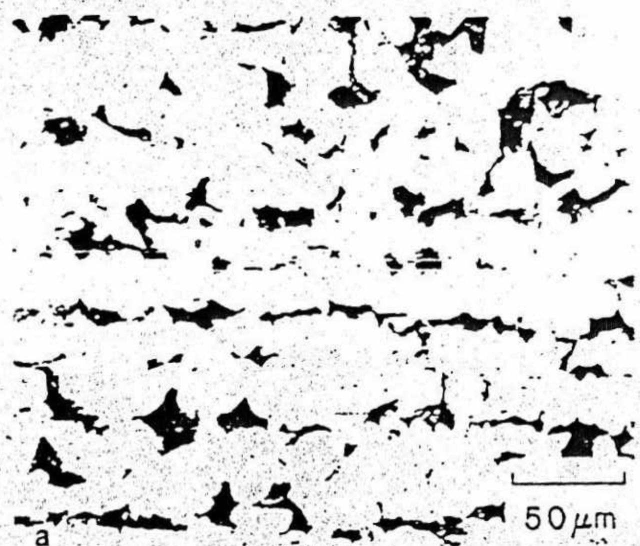
COARSE PEARLITE 38Rc
FINE PEARLITE 45Rc
MARTENSITE + PEARLITE 54Rc
MARTENSITE 65Rc

HARDNESS INCREASES

Normalising & Hardening

Normalising

- micro fine P + Ferrite
- air hardening steels : box cooled else air cooling
- banding/forged structure/ingotism Homogenisation
- strength + toughness
- machinability of low C steel
- carbide network eliminated



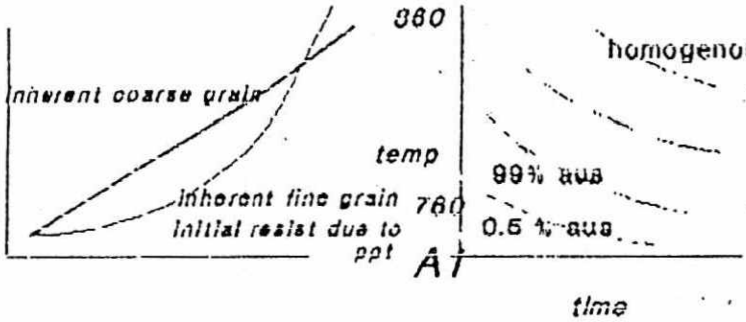
BANDING IN A 0.25%CS

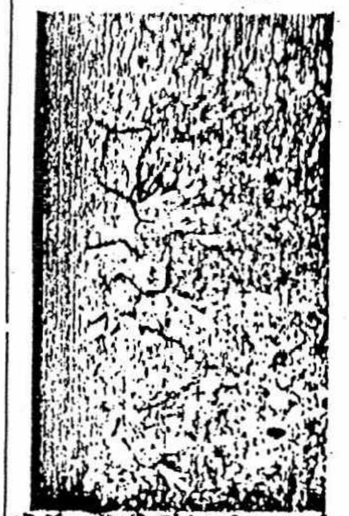
Hardening

- Temperature : hypo UCT; hyper LCT.
- Rapid cool : oil, water, brine
- Martensite : high hardness, strength
- Brittle, internal stress : TEMPERING must

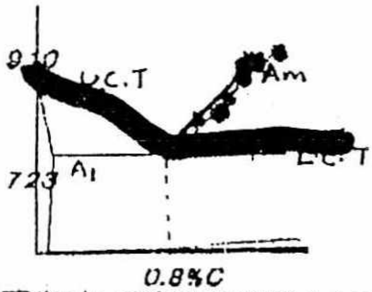
Austentising

- Grain Size = prior austenite g.s.
- ASTM G.Size no.(N)· $n = 2^{N-1}$



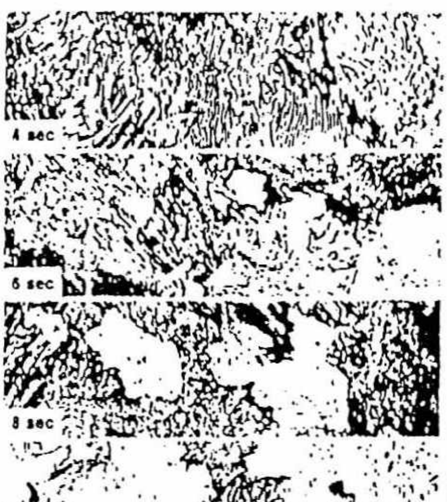


CAVITATION IN [illegible] GRAIN

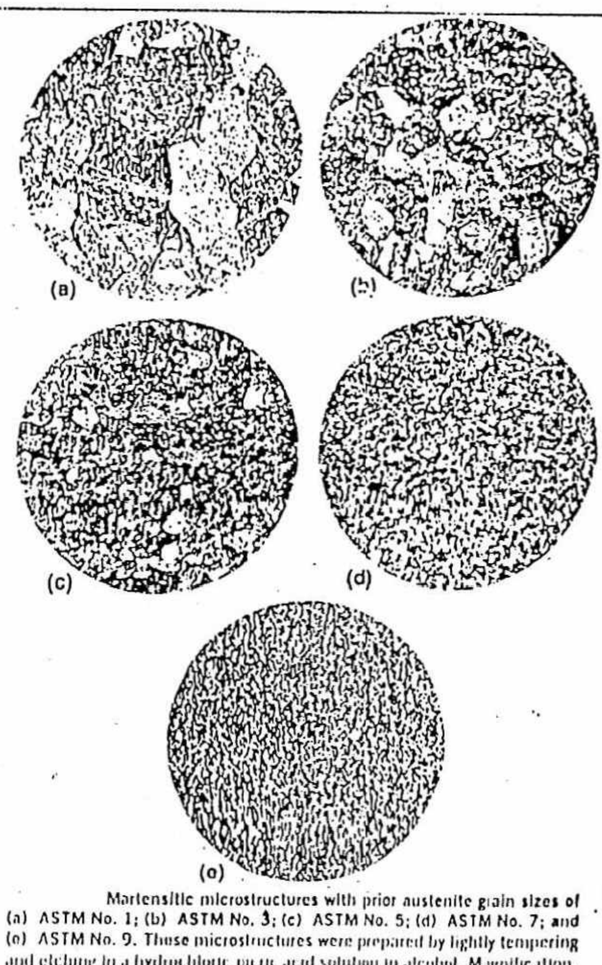


Grain Size Increase :

- *low yield strength*
- *low toughness*
- *hardenability high*
- *intergranular fracture→*
- *coarse ppt*
- *coarse plate martensite*



Formation of austenite (light patches) from pearlite as a function of time. (Ref 7.10)



Martensitic microstructures with prior austenite grain sizes of (a) ASTM No. 1; (b) ASTM No. 3; (c) ASTM No. 5; (d) ASTM No. 7; and (e) ASTM No. 9. These microstructures were prepared by lightly tempering and etching in a hydrochloric picric acid solution in alcohol. Magnification, 100×; shown here at 50%. (Ref 7.10)