MICROSTRUCTURAL CONSTITUENTS IN STEELS

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INTRODUCTION

The structure and properties of various microstructural constituents observed in steels viz. ferrite, cementite, alloy carbides, pearlite, martensite, tempered martensite and bainite are discussed. Typical industrial examples will be cited to indicate how the presence of these phases is effectively made use of by controlling their quantity as well as the size, shape and distribution.

ALLOTROPIC TRANSFORMATION IN IRON

Pure iron has a body cubic structure at ordinary temperatures and is ferromagnetic with a curie temperature of 768°C. The magnetic and non-magnetic forms are generally referred to as α-iron and β-iron respectively. Iron changes to the face-centered cubic form (γ) on heating to 910°C and then back to the b.c.c. form (δ) at 1400°C.

FERRITE

Ferrite is the solid solution of carbon and/or alloying elements in the b.c.c. form of iron and is represented by the symbol, α. It is the softest of all the phases present in steels. Its yield strength depends on the following factors :

(a) grain size (b) solid solution strengthening (c) prior strain.

The yield strength (a) increases with decreasing grain size according to the Hall-Petch equation.

$$\alpha = \alpha_i + K_y d^{-1/2}$$

where d is the grain diameter and α_i and K_y are constants. Fig.1 shows that the YS can be considerably increased by lowering the grain size (a fact that is extensively made use of HSLA) steels by micro-alloying with Nb or V and also by thermo-mechanical processing).

The interstitial elements (C & N) as well as substitutional elements also increase significantly the YS or hardness as shown in Figs. 2 and 3 for carbon and substitutional elements respectively. The effect of the interstitial elements is much more noticeable but their solubility in α is very small. Among the substitutional elements, P and Si increase the hardness but lower the toughness considerably. Mn is the most desirable element to increase the hardness as well as the toughness of ferrite and thus becomes an important alloying element in HSLA steels.

Prior cold work increases the density of dislocations (Fig.4) and thus leads to a considerable increase in strength. Fig.5 shows the increase in the strength of a low carbon steel due to wire drawing.

CEMENTITE & ALLOY CARBIDES

Cementite (Fe_3C), the equilibrium iron carbide, is hard (about 850 VHN) and brittle. It occurs as a microconstituent in hyper eutectoid steels either as spheroidised carbide (Fig.6) or as the grain boundary phase (Fig.7). Spheroidised structures are the easily machined ones in tool steels. Grain boundary cementite makes the steel extremely brittle. In hypoeutectoid steels cementite forms as an important phase in pearlite.

In alloy steels containing carbide forming elements (Cr, Mo, W, V, Ti, Nb), alloy carbides occur with much higher hardness values. Cr forms Cr_7C_3 and $Cr_{23}C_6$, Mo and W form Mo C/WC and Mo_2C/W_2C and V, Nb and Ti form MC type carbides. The hardness as well as stability of these carbides is in the order given. In addition, ternary carbide of the alloying element with Fe forms in some Mo or W steels as M_6C. It is obvious that the presence of these hard carbides in ferrite increases its strength and wear resistance.

PEARLITE

Pearlite is the eutectoid decomposition product of austenite and consists of alternate lamellae of ferrite and cementite. The eutectoid reaction taken place at 768°C and 0.8 % C. The hardness and strength of pearlite depends on the interlamellar spacing, λ, which itself depends on the degree of undercooling ($\Delta T = T_c$-T) which is the difference between the eutectoid temperature (T_c) and the transformation temperature (T) :

$$\lambda = 4\sigma T_c / \Delta H.\Delta T$$

where σ is the interfacial energy per unit area of the α/Fe_3C boundary and ΔH is change in enthalpy per unit volume between γ and pearlite. Fig.8 shows the variation of λ with ΔT.

The hardness of pearlite decreases gradually with increasing interlamellar spacing, i.e., increasing temperature of transformation as is shown in a TTT curve in Fig.9. The toughness of a steel, as indicated by either the DBTT or upper shelf energy, decreases as the pearlite content (% carbon) increases (Fig.10).

The presence of carbide forming elements increases the hardness of pearlite considerably by changing the chemistry of carbide and drastically lowering λ and such steels may have hardness of more than 400 VHN. Elements like Ni or Si increase the hardness of pearlite slightly by decreasing λ and increasing the strength of ferrite by solid solution strengthening.

most of the medium carbon and alloy steels are extensively used for various structural applications (they become economical as one need not use expensive heat treatment operations to get these microstructures) and fully pearlitic steels are commonly used for applications such as rails and wire ropes.

MARTENSITE

When a steel is cooled fast enough (quenched) so that it escapes the most of the TTT curve (Fig.9), the austenite transforms to martensite by a shear mechanism without involving any diffusional processes. The martensite thus formed is a supersaturated solid solution of carbon in α-iron and is different morphologically and crystallographically from ferrite. In carbon steels the martensite is body-centered tetragonal in structure whose tetragonality increases with increasing carbon :

$$c/a = 1 + 0.045 X$$

where x is weight per cent carbon.

Morphologically, martensite has a shape of lenticular plates in high carbon steels (above 1% C) and is lath shaped in steels upto 0.6% C with a mixed morphology in a intermediate range (Figs.11).

The lath martensite comprises laths of 0.25 - 0.5μm width, with a high density of dislocations (Fig.12) while the plate martensite consists of twin with or without dislocations as the substructure (Fig.13).

The hardness of martensite depends significantly on the carbon content (due to interstitial solid strengthening) as shown in Fig.14 (which also shows the hardness of annealed and normalised steels as a function of carbon content). The ductility and toughness of martensite decrease with increasing carbon, making medium and high carbon steels brittle. Quenched steels are therefore invariably tempered to restore toughness.

C-4

TEMPERED MARTENSITE

Tempering is the process of reheating a quenched steel below the A_1 temperature to restore toughness. Tempering takes place in three or four stages depending on whether the steel is a plain carbon or an alloy steel. The first stage of tempering which occurs upto about 200°C, consists of the precipitation of ε-carbide as extremely fine needles of 50 - 100A° diameter (Fig.15). The hardness is not significantly altered during this stage (Fig.16) but the volume as well as the magnetic saturation intensity decrease. The transformation of retained austenite to ferrite and cementite (or low carbon martensite and α-carbide) constitutes the second stage of tempering that occurs between 200 and 768°C. Since retained austenite occurs in small quantities in most low carbon low alloy steels, this stage also does not cause a noticeable change in hardness or strength but the formation of cementite films along the lath boundaries of martensite during the second stage causes a loss in toughness when tempered at a temperature of about 300°C. (Fig.17). This is known as "tempered martensite embrittlement".

On tempering at temperatures greater than 300°C, the third stage of tempering starts with the precipitation of cementite along the lath boundaries as well as within laths (Fig.18), which coincides with the onset of softening. Increasing the temperature results in coarsening of cementite platelets upto about 450°C beyond which they tend to spheroidise (to minimise the surface energy). Ultimately when the tempering temperature is increased to 700°C, the cementite spheroids can be seen in an optical microscope (Fig.6). The hardness continues to fall throughout the third stage of tempering.

In alloy steels containing carbide forming elements, a fourth stage of tempering occurs leading to the precipitation of extremely fine alloy carbides at the expense of cementite. Since these carbides

are coherent with the matrix, they cause precipitation hardening to increase the hardness of the steel (Fig.19). This is known as secondary hardening' and occurs at about 500°C for Cr steels, 550°C for Mo and W steels and 600°C for steels containing V or Nb for normal tempering times of an hour.

Although the toughness of steels increases gradually with increasing temperature beyond 300°C, certain alloy steels exhibit a decrease in toughness when tempered at about 475-525°C (Fig.20). This phenomenon, known as "embrittlement", is a serious problem in alloy steels.

It is now well established that temper brittleness is found in: (a) alloy steels containing Ni, Mn and Cr and not in plain carbon steels, (b) air melted steels and not in high purity vacuum melted steels.

It is found that the steels subjected to temper embrittlement exhibit a shift in the impact toughness curves to higher temper temperatures (to result in a higher ductile-brittle transition temperature) and reveal intergranular fractures. It has also been well established with the help of Auger electron spectroscopy that temper embrittled steels exhibit co-segregation of impurity elements (As, Sn, Sb, Bi and P) along with the alloying elements (Ni or Mn) at prior austenite grain boundaries.

It is therefore imperative that to avoid temper embrittlement, alloy steels have to be preferably vacuum melted or should be cooled fast after tempering at higher temperatures. It has been also found that addition of 0.25% Mo to alloy steels decrease the sensitivity of steels to temper embrittlement.

Quenching and tempering treatment result in the best combination of strength and toughness in carbon or alloy steels and are thus extensively used for structural applications such as in automobile

industry. They are also commonly used for tool steels where high hardness and wear resistance are desired. The main limitation is that the heat treatments are expensive.

BAINITE

When a carbon or alloy steel is rapidly cooled to a temperature below that of pearlite formation, but above that of martensite formation, and is held at that temperature, the austenite decomposes isothermally to bainite. Bainite is non lamellar decomposition product of austenite formed in the temperature range of 550°C. (note of the TTT curve) and the M_s temperature. Within this range two morphologies of bainite have been found. These are called upper bainite (the feathery bainite was used in the earlier years) and lower bainite (acicular bainite) as shown in Figs.21 and 22 respectively. The former consists of ferrite laths with cementite along the lathe boundaries while the lower bainite comprises ferrite plates with cementite platelets at an angle of about 55° to the plate boundaries. Although bainite is formed in plain carbon steels by isothermal transformation (not continuous cooling) of austenite only, it may form by continuous cooling in some alloy steels due to the preferential delay in ferrite formation by these elements. Bainitic structures result in intermediate strengths and toughness values between those of tempered martensites and ferrite-pearlite structures (Fig.23).

In some low carbon low alloy steels bainitic structures can be obtained by continuous cooling from the austenitic state and such microstructures are referred to as granular bainites. When the carbon content in such steels is very low (below 0.05%), they are termed as acicular ferrites because of the acicular morphology and the extremely small volume fraction of carbides in them. Acicular ferrite structures have a good combination of strength and toughness.

Bainitic structures are commonly found in some structural steels and high temperature steels (such as rotors and superheater tubes in thermal power plants).

BIBLIOGRAPHY

1. E.C. Bain and H.W.Paxton, Alloying Elements in Steel, ASM, 1961

2. W.C.Leslie, The Physical Metallurgy of Steels, McGraw-Hill, 1981

3. G.Krauss, Principles of Heat Treatment of Steel, ASM 1980

4. ASM Metals Handbook, Desk Ed. 1985

5. F.B. Pickering, Physical Metallurgy and the Design of Steels, Applied Science, 1978

6. K.E. Thelning, Steel and Its Heat Treatment, Butterworths, 1984

7. ASM: Metals Handbook, Vol.7 Ed.B, 1972

8. W.F.Smith, Structure and Properties of Engineering Alloys, McGraw-Hill, 1993

9. D.S.Sarma, Banaras Metallurgist, Vol.5, 1973 p55.

10. R.Wilson, Metallurgy and Heat Treatment of Tool Steels, McGraw-Hill, 1975.

FIGURE CAPTIONS

Fig.1   The effect of grain size on the lower yield point of α-iron (ref2, p20).

Fig.2   Influence of dissolved carbon on the yield strength of α-iron (ref 1, p62).

Fig.3   Solid solution strengthening of ferrite due to alloy elements (ref 5,p11).

Fig.4   Dislocation structure in α-iron cold rolled to 9%   (ref2 p10).

Fig.5   Effect of prior strain on the UTS of iron (ref2,p9).

Fig.6   Spheroidised structure in a1% C steel (ref 1p 101).

Fig.7   Normalised structure in a 1% C steel showing cementite along prior austenite grain boundaries (ref.7, p50).

Fig.8   Effect of undercooling on the interlamellar spacing of pearlite (ref.3, p26).

Fig.9   TTT diagram of a eutectoid steel showing the influence of transformation temperature on the hardness (ref.4, p28.4).

Fig.10   Effect of carbon on the impact toughness of Steels (ref.5, p95).

Fig.11   Influence of carbon on the morphology of martensite (ref.4, p28.6).

Fig.12   Lath martensite structure in a low carbon steel (ref 9).

Fig.13   Plate martensite structure in an Fe-24 Ni-0.5C alloy (ref.9).

Fig.14   Influence of carbon on the hardness of martensite and pearlite (ref.4, p.28.9).

Fig.15 ε-carbide precipitation in an Fe-24Ni-0.5C alloy on tempering at 205°C (ref 8, p67).

Fig.16   Tempering curve of a eutectoid steel (ref 10. 0p46).

Fig.17   Cementite precipitation in a medium carbon steel on tempering at 768°C. (ref.8. p68).

Fig.18   Tempered martensite embrittlement in a low alloy steel (ref6, p299).

Fig.19   Secondary hardening effects of molybdenum in a 0.3C-2Cr steel (ref.p201.

Fig.20   Temper embrittlement in a H11 steel (ref 6, p301).

Fig.21   Upper bainite structure in a 1087 steel transformed at 455°C (ref 1, p268).

Fig.22   Lower bainite structure in a 1087 steel transformed at 315°C (ref1 p269).

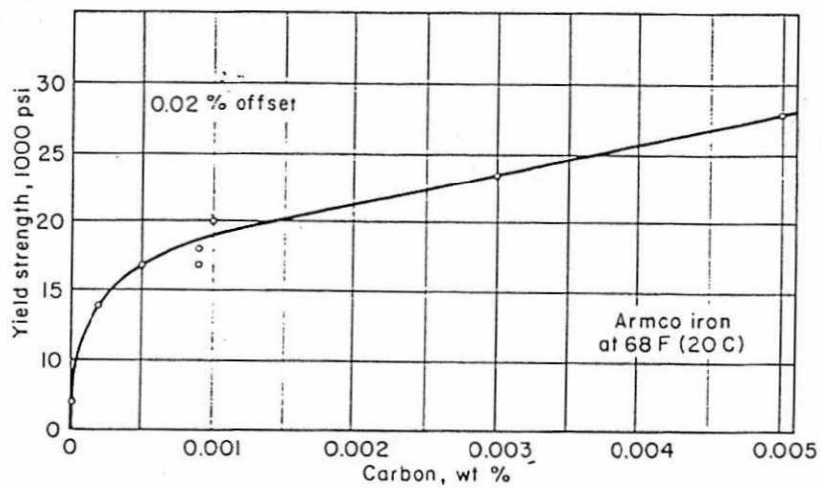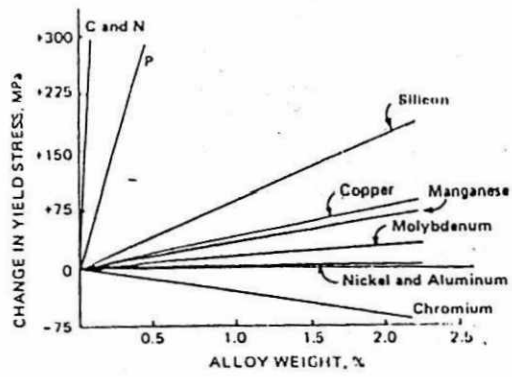Fef.23   Influence of transformation temperature on the tensile strength of steels ref 5, p33).
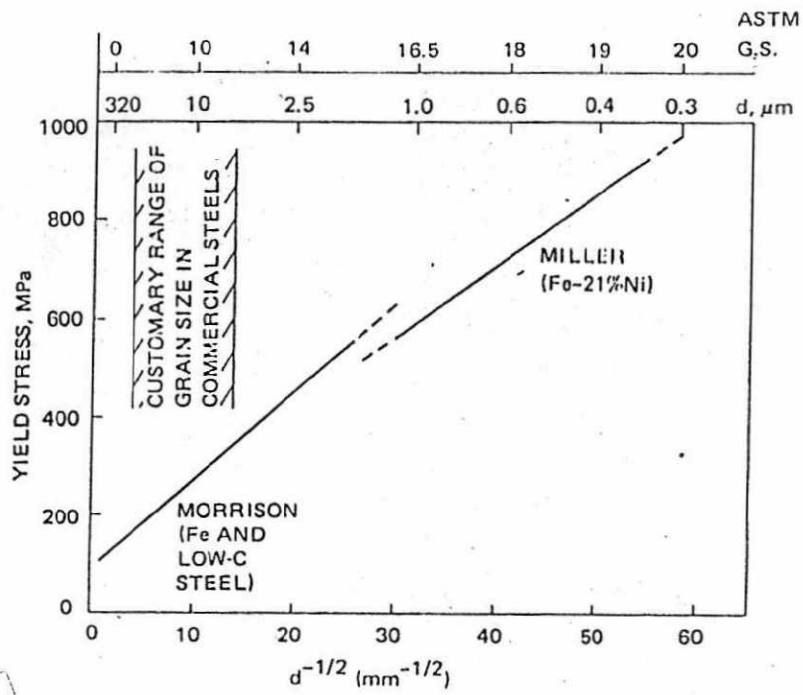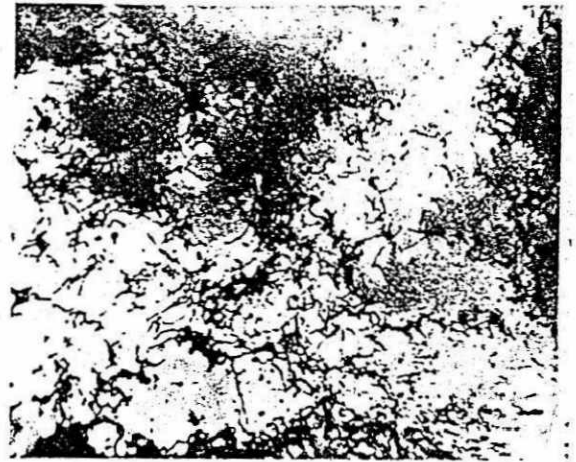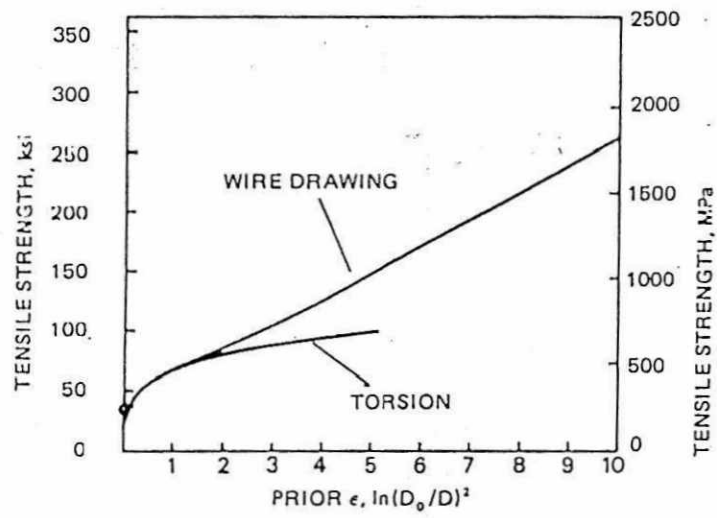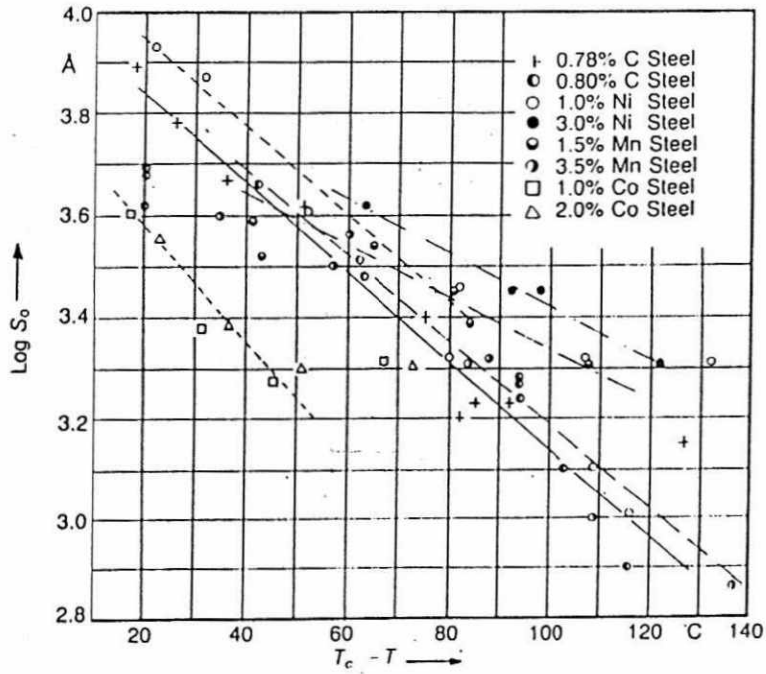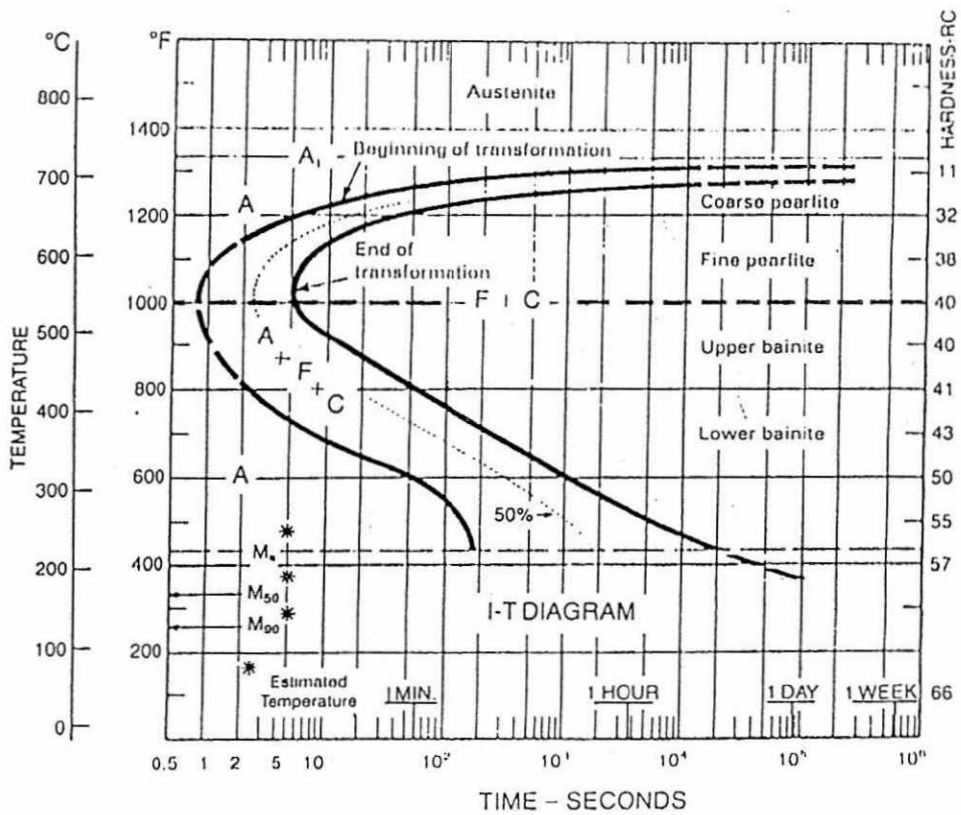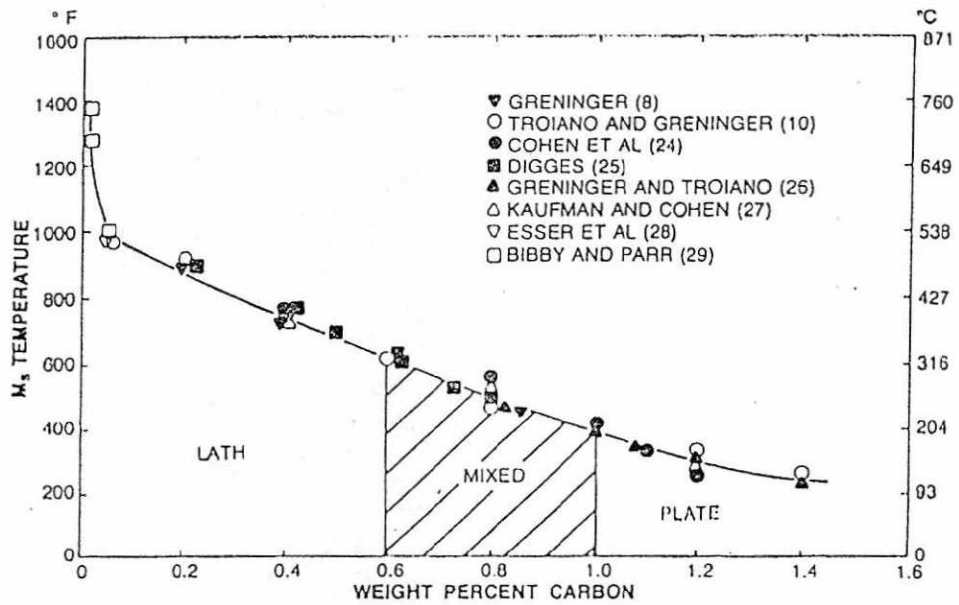
Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Log S_o (A) vs $T_c - T$ (°C)

Legend:
- 0.78% C Steel
- 0.80% C Steel
- 1.0% Ni Steel
- 3.0% Ni Steel
- 1.5% Mn Steel
- 3.5% Mn Steel
- 1.0% Co Steel
- 2.0% Co Steel

Y-axis: Log S_o — values 2.8, 3.0, 3.2, 3.4, 3.6, 3.8, 4.0

X-axis: $T_c - T$ — values 20, 40, 60, 80, 100, 120, 140 °C

Fig. 8

Fig. 9

I-T DIAGRAM

°C / °F (TEMPERATURE) vs TIME – SECONDS, HARDNESS-RC

Austenite

A_1 — Beginning of transformation

A — Coarse pearlite

End of transformation

$A + F + C$

$F + C$

50%

A

M_s

M_{50}

M_{90}

Estimated Temperature

Coarse pearlite
Fine pearlite
Upper bainite
Lower bainite

Temperature axis (°C): 800, 700, 600, 500, 400, 300, 200, 100, 0
Temperature axis (°F): 1400, 1200, 1000, 800, 600, 400, 200

Hardness-RC: 11, 32, 38, 40, 40, 41, 43, 50, 55, 57, 66

Time axis: 0.5, 1, 2, 5, 10, 10^2, 10^1, 10^4, 10^5, 10^6
1 MIN., 1 HOUR, 1 DAY, 1 WEEK

Fig. 9

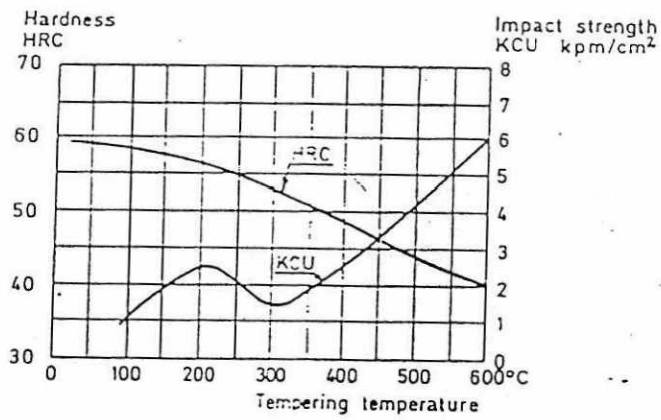Fig. 10

Fig. 11

Fig. 12

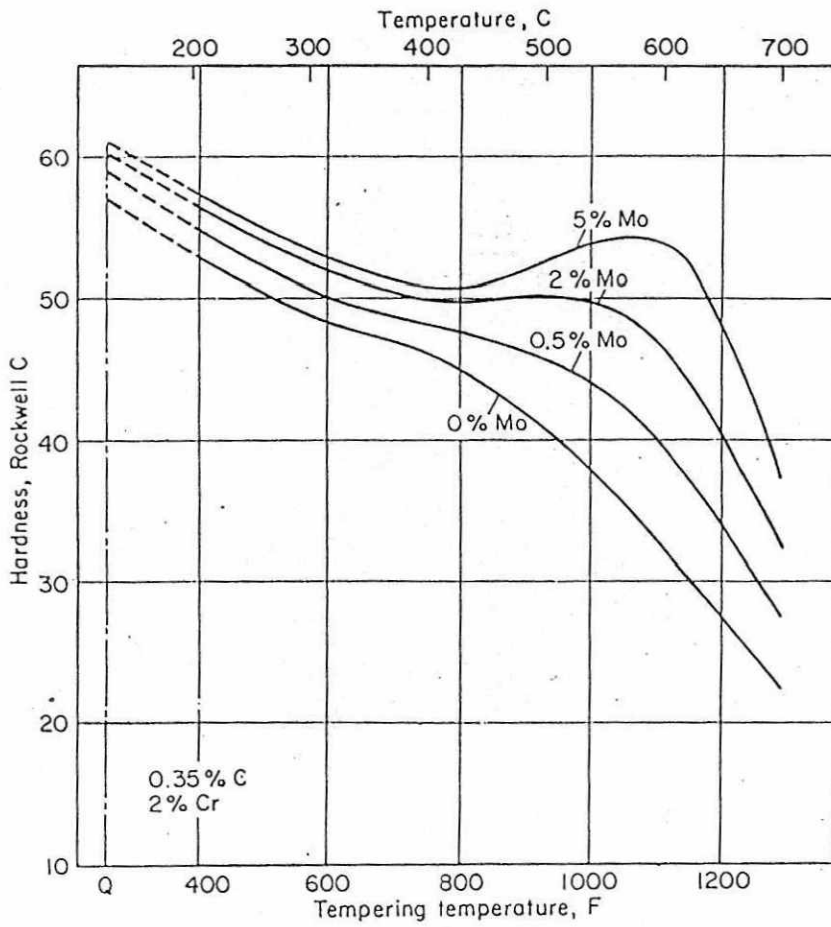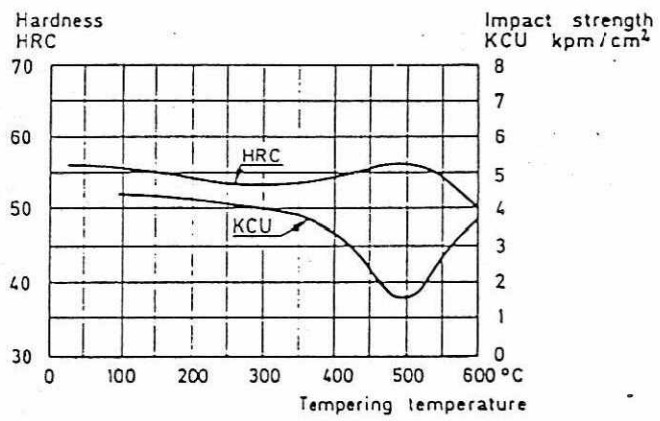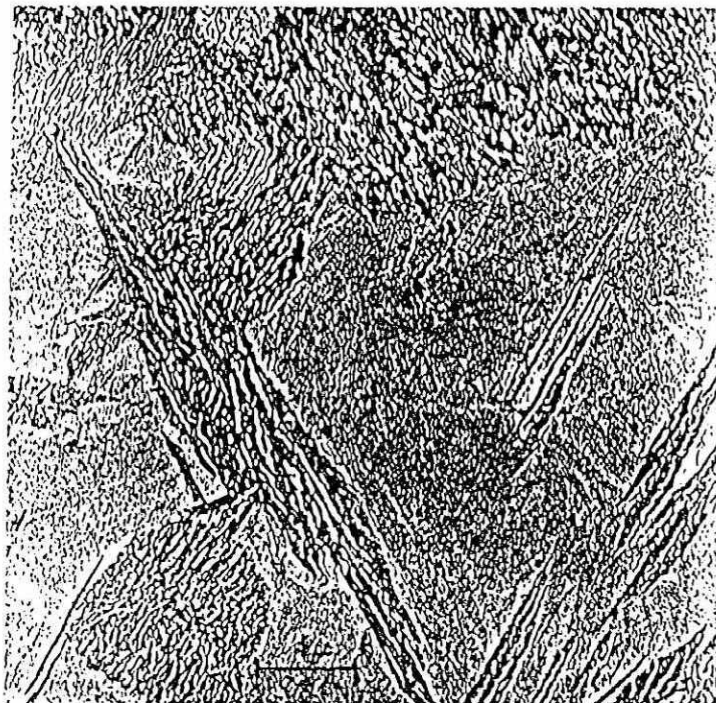Fig. 13
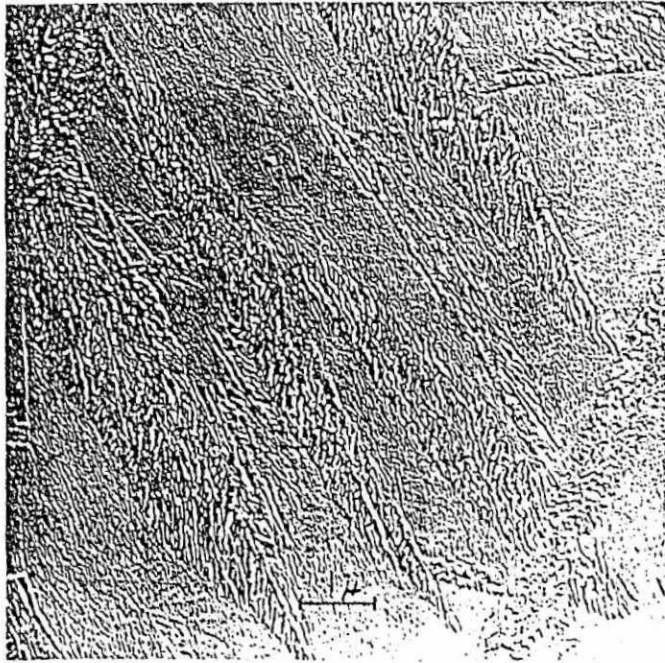

Fig. 14

0.5 μm
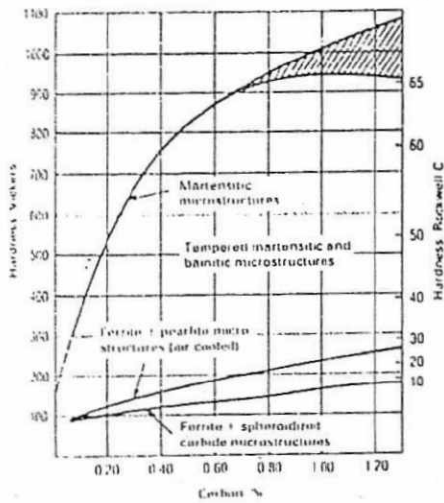
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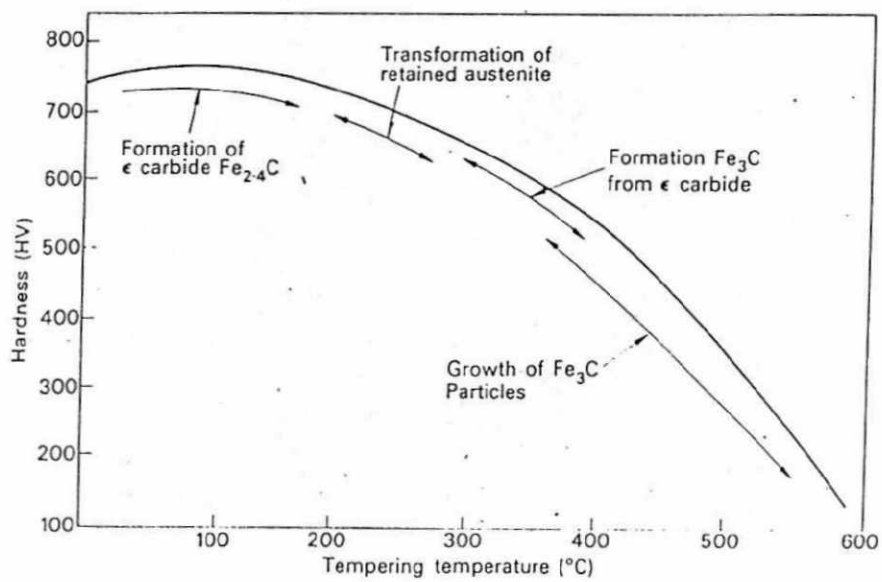
Fig. 16

Fig. 18

Fig. 17

Fig. 19

Fig. 20

Fig. 21

Fig. 22

Fig. 23