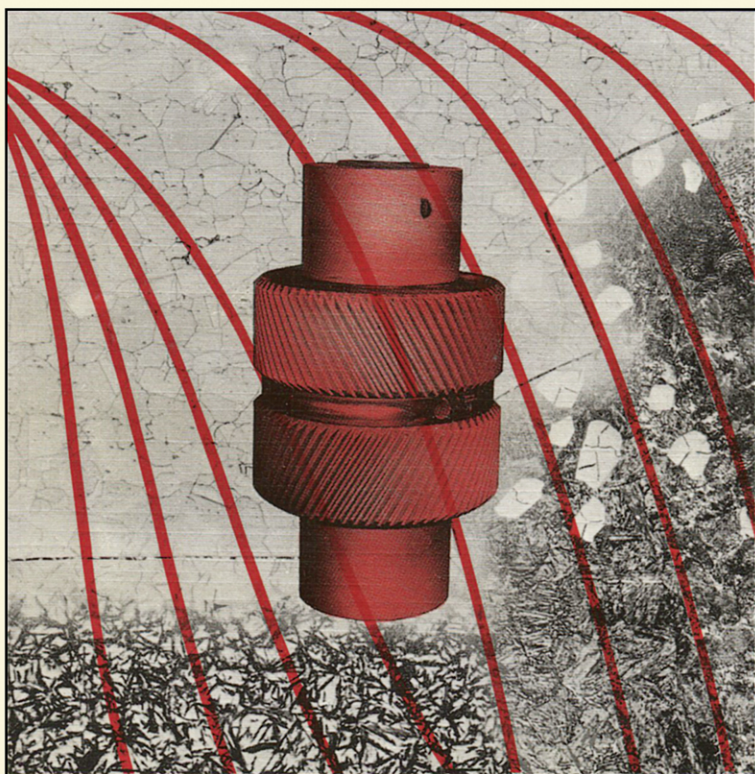


Steel and its Heat Treatment



BOFORS HANDBOOK
K-E Thelning

Butterworths

Steel and its Heat Treatment

Bofors Handbook

The cover illustration shows a CCT diagram with the different microstructures occurring during quenching. On the left are surface cooling curves and, on the right, centre cooling curves with a typical component for heat treatment superimposed.

Steel and its Heat Treatment

Bofors Handbook

KARL-ERIK THELNING

*Formerly Head of Development for Constructional and Tool Steels,
A. B. Bofors*

Currently Chief Metallurgist, Boxholm

Butterworths

London Boston Sydney Wellington Durban Toronto

All rights reserved. No part of this publication may be reproduced or transmitted in any form or by any means, including photocopying and recording, without the written permission of the copyright holder, application for which should be addressed to the Publishers. Such written permission must also be obtained before any part of this publication is stored in a retrieval system of any nature.

This book is sold subject to the Standard Conditions of Sale of Net Books and may not be re-sold in the UK below the net price given by the Publishers in their current price list.

© English translation
Aktiebolaget Bofors 1975

English edition first published 1975
Reprinted 1978
Reprinted 1981

ISBN 0 408 70934 0

This book is the revised English version of
Bofors Handbook: Värmebehandling av Stål
published in Sweden by Maskinaktiebolaget Karlebo in 1967

© A. B. Bofors and Maskinaktiebolaget Karlebo 1967

Printed in England by Fakenham Press Ltd, Fakenham, Norfolk

Preface

The need for a handbook, which provides practical information together with references to theoretical work, continues to increase in steel-consuming industries. *Steel and its Heat Treatment: Bofors Handbook* has been written to meet this need and especially to bridge the widening gap between practical and theoretical knowledge.

The original Swedish edition (1967), which was received with great interest, was written on the initiative of Mr Tord Krey, Director of Research of AB Bofors and was sponsored by the Swedish Metallographers Society. The contents of that edition were checked by Mr Sven Arwidson, Chief Metallurgist of AB Bofors, together with Mr Göran Larsson and Mr Kurt Walter.

In the years since the publication of the Swedish edition the author has been in contact with several readers and their opinions have influenced the contents of the present edition, which has also been carefully revised and supplemented to meet both the demand for recent information and the requirements of students.

This English edition has been checked by Professor Bertil Aronsson, Head of the Swedish Institute for Metal Research, Dr J. A. Charles, University of Cambridge, and Dr Tom Bell, University of Liverpool. The translation was made under the supervision of the Metals Society, formerly The Iron and Steel Institute, mainly by Mr Cecil M. Black.

The author wishes to thank all persons and institutions mentioned above and all others who have assisted or contributed to the publication of this English edition of the *Bofors Handbook*.

Bofors 1974

Karl-Erik Thelning

International Designations and Symbols

INTERNATIONAL SYSTEM OF UNITS

On the 1st of January 1971 the metric system was legally in force in the U.K. For the majority of technicians this involved an adjustment from inches to millimetres. For several years, work has been in progress to devise a common standard international system of units. Such a system, SI (Système International d'Unités), was adopted in 1960.

The following units should be used in ISO Recommendations prepared under the jurisdiction of ISO/TC 17:

1. Stress — N/mm^2
2. Hardness—There should be no change in the present practice in that the load applied to the indenter should still be expressed in terms of the unit kgf.
3. Impact —In general it was agreed that the joule should be used, but in some cases the Nm might be a preferable unit.

During an interim period several European countries have used the symbol kp/mm^2 (kilopond) or kgf/mm^2 (kilogramme-force) to signify the unit of stress.

The mechanical strength of steel was previously designated ton/in^2 (TSI) in the UK and kg/mm^2 on the Continent.

The present book has been written and published during the period of transition covering the introduction of SI units both in the UK and other countries that have adopted it. In several diagrams in this book stress is designated kp/mm^2 and in some tables, kgf/mm^2 in accordance with some editions of ISO's recommendations. (B.S. 970:1970 gives kgf/mm^2 as the designation for stress.)

In order to simplify the transition to SI units most diagrams have been drawn with double scales, e.g. inches–millimetres, kp/mm^2 – TSI – N/mm^2

INTERNATIONAL DESIGNATIONS AND SYMBOLS

and even Celsius (°C)–Fahrenheit (°F). The symbol joule is not always adopted here since, the final decision will be taken at the end of 1974.

In some tables two systems of units are used. For the conversion of inches to millimetres the factor 25.0 has often been used since the small error introduced thereby is of no practical consequence. For other, more precise applications, such as for Jominy diagrams, the exact conversion factor has been used.

In other ways, too, an international outlook is favoured, viz. the symbols for hardness units, e.g. HB and HRC. In line with this principle the symbol HV is used instead of DPH or VPN. Conversion tables and nomograms are found in Chapter 8.

In connection with passing over to SI units, according to the ISO standard a number of designations for mechanical testing has been changed. What is characteristic of this transition is that certain designations in Greek letters have been replaced by Latin ones. The designations generally used for steel are indicated below, partly old ones, partly according to the new standard. An example for the use of SI units is given at the same time.

Old standard

$\sigma_{0.2}$ kp/mm ²	σ_B kp/mm ²	σ_5 %	ψ %	HB	KV kpm	KCU kpm/cm ²
54	81	19	61	249	7,0	9,2

New standard—SI

$R_{p0.2}$ N/mm ²	R_m N/mm ²	A_5 %	Z %	HB	KV J	KU J
530	790	19	61	249	69	45

In old ISO documents cited in this book the proof stress is designated by R_e . The designation $R_{p0.2}$ was adopted in 1973.

INTERNATIONAL STEEL DESIGNATIONS

Under the auspices of ISO extensive work is in progress on the standardization of steel grades, in particular with respect to composition and mechanical properties. ISO recommendations covering a large number of steel grades have already been published. Among them may be mentioned the group 'heat-treated steels, alloy steels and free-cutting steels'. The work of standardization for tool steels should be completed by 1976.

The tables covering 'Surveys of various types of steel' contain the standards as published by AISI, BS, DIN and SIS along with such ISO standards as have been issued.

In the text, tool steels are designated only by the type letter and numeral as used in the USA and the UK for standardized tool steels, e.g. H 13, O 1. These designations are so well known by steel consumers all over the world that no qualifying institutional designations are necessary. Steels for which there are no AISI or BS specifications are designated according to DIN or SIS standards.

INTERNATIONAL DESIGNATIONS AND SYMBOLS

Depending on which steel types are being discussed in the text, constructional steels are designated according to BS standards as well as AISI, DIN or SIS standards, respectively.

It is the author's aim and hope that this book will help in promoting the introduction of the SI units and the adoption of the international steel designations.

Contents

1	Fundamental metallographic concepts	1
1.1	The transformation and crystal structures of iron	1
1.2	The iron–carbon equilibrium diagram	4
1.2.1	Heating	5
1.2.2	Cooling	6
1.3	Time–temperature–transformation	6
1.3.1	Heating	7
1.3.2	Cooling	13
1.3.3	Formation of pearlite	13
1.3.4	Formation of bainite	14
1.3.5	Formation of martensite	15
1.3.6	Retained austenite	18
1.3.7	TTT diagrams	20
1.4	Decomposition of martensite and retained austenite on tempering	20
1.5	Diffusion	23
1.5.1	The nature of diffusion	23
1.5.2	Factors that influence the rate of diffusion	24
1.5.3	Calculation of diffusion distance	25
1.6	Dislocations	29
1.7	Grain size	32
1.7.1	Grain boundaries	32
1.7.2	Methods of determining grain size	34
1.7.3	Examples of grain size determinations	38
2	Materials testing	42
2.1	The hardness test	42
2.1.1	The Brinell test	42

CONTENTS

2.1.2	The Vickers test	43
2.1.3	The Knoop test	44
2.1.4	The Rockwell test	44
2.1.5	The Scleroscope test	47
2.1.6	Conversion tables for various scales of hardness	49
2.2	The tensile test	51
2.2.1	Comparison between mechanical properties obtained according to different specifications	53
2.3	The impact test	53
2.4	The torsion impact test	57
2.5	The fatigue test	58
2.5.1	Fatigue in general	58
2.5.2	Test procedure	60
2.5.3	Different types of fatigue fractures	62
2.5.4	Goodman diagram	64
2.5.5	Endurance limit—ultimate tensile strength	65
2.5.6	Surface finish	66
2.5.7	Influence of change of section	69
2.5.8	Ways of increasing the endurance limit	69
2.6	The creep test	69
2.7	Brittle and ductile fractures	72
2.8	Fracture toughness	76
2.8.1	The implication of fracture toughness	80
3	Alloying elements in steel	82
3.1	Solids	82
3.1.1	Austenite-forming elements	82
3.1.2	Ferrite-forming elements	83
3.1.3	Multi-alloyed steels	84
3.1.4	Carbide-forming elements	85
3.1.5	Carbide stabilizers	85
3.1.6	Nitride-forming elements	86
3.1.7	Effect on ferrite hardness	87
3.1.8	Effect on grain growth	88
3.1.9	Effect on the eutectoid point	89
3.1.10	Effect on the temperature of martensite formation	90
3.1.11	Effect on the formation of pearlite and bainite during the isothermal transformation	93
3.1.12	Effect on resistance to tempering	102
3.2	Gases	106
3.2.1	Hydrogen	106
3.2.2	Nitrogen	110
3.2.3	Oxygen	113
3.3	New steelmaking processes	116
3.3.1	Vacuum remelting	116
3.3.2	Electroslag refining	117

3.3.3	Vacuum degassing	120
3.3.4	The Bofors method of sulphur removal	121
3.3.5	Effect of sulphur on the properties of steel	121
4	Hardenability	127
4.1	General remarks	127
4.2	The Grossmann hardenability test	130
4.2.1	Calculation of D_I -values from chemical composition	132
4.3	The Jominy end-quench hardenability test	137
4.3.1	Calculation of Jominy curves from the chemical composition	140
4.3.2	Practical applications of Jominy curves	141
4.4	Practical application of the TTT and the CCT diagrams	151
4.5	Practical application of hardenability	161
4.5.1	High hardenability	161
4.5.2	Low hardenability	163
4.6	The influence of the depth of hardening on the stress pattern	169
5	Heat treatment—general	177
5.1	Annealing	177
5.1.1	Annealing for maximum softness or spheroidizing anneal	177
5.1.2	Recrystallization annealing	184
5.1.3	Stress-relief annealing	184
5.1.4	Isothermal annealing	188
5.1.5	Quench annealing	188
5.1.6	Homogenizing annealing	191
5.1.7	Hydrogen annealing	191
5.1.8	Hydrogen expulsion	191
5.2	Normalizing	191
5.3	Hardening	194
5.3.1	Heating media	194
5.3.2	Rate of heating	202
5.3.3	Hardening temperature	206
5.3.4	Holding time at temperature	209
5.3.5	Methods of cooling	212
5.3.6	Quenching media	219
5.3.7	Quenching equipment	230
5.4	Tempering	233
5.4.1	Heating to temperature	234
5.4.2	Rate of heating	234
5.4.3	Holding time	240
5.4.4	Double tempering	244
5.4.5	Temper brittleness	246

CONTENTS

5.5	Transformation of retained austenite	249
5.6	Precipitation hardening	253
5.7	Straightening	257
5.8	Machining allowances	258
6	Heat treatment—special	261
6.1	Hardening and tempering of tool steels	261
6.1.1	Carbon steels and vanadium-alloyed steels	261
6.1.2	Low-alloy cold-work steels	266
6.1.3	Low-alloy cold-work and hot-work steels	273
6.1.4	High-alloy cold-work steels	276
6.1.5	Hot-work steels	290
6.1.6	High-speed steels	313
6.2	Quenching and tempering of constructional steels	319
6.2.1	Definitions	319
6.2.2	Plain carbon steels	320
6.2.3	Alloy steels	324
6.2.4	Stainless steels	330
6.2.5	Spring steels	333
6.2.6	High-strength steels	335
6.2.7	Hadfield steel	339
6.3	Case hardening	339
6.3.1	Definitions	339
6.3.2	Grades of steel	342
6.3.3	Methods of carburizing	345
6.3.4	Influence of heat treatment and steel composition on case depth, surface hardness and core hardness	359
6.3.5	Recommendations for case hardening	370
6.3.6	Case hardening of tool steels	371
6.3.7	Protecting against carburization (selective carburizing)	372
6.3.8	Choice of case-hardening depth	374
6.4	Nitriding	377
6.4.1	Methods of nitriding	379
6.4.2	Comparison between gas and salt-bath nitriding	387
6.4.3	Nitridability	395
6.4.4	Determination of depth of nitriding	406
6.4.5	Nitriding different types of steel	407
6.4.6	Properties of nitrided steels	418
6.5	Carbonitriding	427
6.5.1	Definition	427
6.5.2	Theoretical background	427
6.5.3	Conclusions	432
6.6	Induction hardening	432
6.6.1	Fundamental principles	432
6.6.2	Steel grades for induction hardening	435
6.6.3	Equipment for induction hardening	435

6.6.4	Working coils and fixtures	436
6.6.5	Procedure during induction hardening	437
6.6.6	The influence of various factors on hardness and depth of hardening	440
6.6.7	Examples of induction-hardened machine components	447
6.6.8	Advantages and disadvantages of induction hardening	450
6.7	Flame hardening	451
6.7.1	Methods of hardening	451
6.7.2	Hardness and depth of hardening	454
6.7.3	Examples of flame-hardened machine components and tools	458
7	Dimensional changes during hardening and tempering	466
7.1	Dimensional changes during hardening	466
7.1.1	Thermal stresses	466
7.1.2	Transformation stresses	467
7.2	Dimensional changes during tempering	472
7.2.1	Changes in volume	472
7.2.2	Changes in stress conditions	473
7.3	Examples of dimensional changes during the hardening and tempering of tool steels	474
7.3.1	Plain carbon steels	475
7.3.2	Low-alloy steels	476
7.3.3	High-alloy cold-work steels	490
7.3.4	Hot-work steels	496
7.3.5	High-speed steels	502
7.4	Dimensional changes during case hardening	506
7.5	Dimensional changes during nitriding	514
7.6	Ageing	520
7.7	Designing for heat treatment	523
8	Tables	528
8.1	Some steel standard specifications and comparable Bofors and Uddeholm (UHB) steels	528
Table 8.1	American Steel Standard Specifications	529
Table 8.2	British Steel Standard Specifications	529
Table 8.3	German Steel Standard Specifications	530
Table 8.4	Swedish Steel Standard Specifications	531
Table 8.5	Afnor Designations (French)	532
Table 8.6	ASSAB Designations (Associated Swedish Steels AB)	533
8.2	Weight tables for steel bars	534
Table 8.7	Round and Square Bars. Metric Units	534
Table 8.8	Hexagonal and Octagonal Bars. Metric Units	535
Table 8.9	Flat Bars, 10 to 40 mm. Metric Units	535

CONTENTS

	Table 8.10	Flat Bars, 45 to 130 mm. Metric Units	536
	Table 8.11	Flat Bars, 140 to 350 mm. Metric Units	537
	Table 8.12	Round and Square Bars. Inch Units	538
	Table 8.13	Hexagonal and Octagonal Bars. Inch Units	539
	Table 8.14	Flat Bars, Width $\frac{3}{8}$ to $\frac{1}{2}$ in. Inch Units	539
	Table 8.15	Flat Bars, Width $1\frac{5}{8}$ to 5 in. Inch Units	540
	Table 8.16	Flat Bars, Width $5\frac{1}{2}$ to 15 in. Inch Units	541
8.3		Conversion tables for temperature	542
	Table 8.17	Conversion Table for °Celsius (Centigrade) and °Fahrenheit	542
8.4		Conversion table for size	546
	Table 8.18	Inches to Millimetres	546
	Table 8.19	Decimals of Inches to Millimetres	548
8.5		Conversion tables for weight (mass)	549
	Table 8.20	Pounds to Kilogrammes	549
	Table 8.21	British Units to Kilogrammes	550
8.6		Conversion table for stress (pressure)	551
	Table 8.22	Tons per square inch to Kiloponds per square millimetre	551
	Table 8.23	Tons per square inch to Newtons per square millimetre	552
	Table 8.24	Kiloponds per square millimetre to Newtons per square millimetre	553
	Table 8.25	Pounds per square inch to Kiloponds per square millimetre	554
8.7		Conversion tables for energy	555
	Table 8.26	Kilopond metres to Footpounds	555
	Table 8.27	Footpounds to Kilopond metres	556
	Table 8.28	Kilopond metres to Joules	557
	Table 8.29	Footpounds to Joules	558
8.8		Conversion table for fracture toughness units	558
	Table 8.30	Fracture Toughness Units	558
8.9		Conversions for some common units	559
	Table 8.31	Common SI Units to British Units	559
	Table 8.32	Common Non-SI Units to British Units	560
	Table 8.33	Non-SI Metric Units to SI Units	561
8.10		Elements	562
	Table 8.34	Atomic Number and Atomic Weight	562
		Index	563

1

Fundamental metallographic concepts

Metallography reveals the structure of metals and leads to a better understanding of the relationship between the structure and properties of steel. With the aid of modern developments such as the electron microscope and the scanning electron microscope it is now possible to obtain a much deeper insight into the structure of steel than was possible only some ten years ago.

In order to understand the processes occurring during the heat treatment of steel, it is necessary to have some knowledge of the phase equilibriae and phase transformations which occur in steel as well as of its microstructure. Therefore, a brief summary of these topics is given in this chapter which forms the groundwork for subsequent discussion.

1.1 THE TRANSFORMATIONS AND CRYSTAL STRUCTURES OF IRON

On heating a piece of pure iron from room temperature to its melting point it undergoes a number of crystalline transformations and exhibits two different allotropic modifications. When iron changes from one modification to another heat is involved. This is called the latent heat of transformation. If the sample is heated at a steady rate the rise in temperature will be interrupted when the transformation starts and the temperature will remain constant until the transformation is completed. On cooling molten iron to room temperature the transformations take place in the reverse order and at approximately the same temperatures as on heating. During these transformations heat is liberated which results in an arrest in the rate of cooling, the arrest lasting as long as the transformation is taking place.

The two allotropic modifications are termed ferrite and austenite and their ranges of stability and transformation temperatures on heating and cooling are shown in *Figure 1.1*. The letter *A* is from the French *arrêter*, meaning to delay, *c* from *chauffer*, meaning to heat and *r* from *refroidir*, meaning to cool. Ferrite is stable below 911 °C as well as between 1392 °C and its melting point, under the names α -iron and δ -iron respectively.

2 FUNDAMENTAL METALLOGRAPHIC CONCEPTS

Austenite, designated γ -iron, is stable between 911 °C and 1392 °C. Iron is ferromagnetic at room temperature; its magnetism decreases with increasing temperature and vanishes completely at 769 °C, the Curie Point.

The atoms in metals are arranged in a regular three-dimensional pattern called a crystal structure. In the case of iron it may be pictured as cubes stacked side by side and on top of one another. The corners of the cubes are the atoms and each corner atom is shared by eight cubes or unit cells. Besides the corner atoms the iron unit cell contains additional atoms, the number and positions of which depend on the modification being studied.

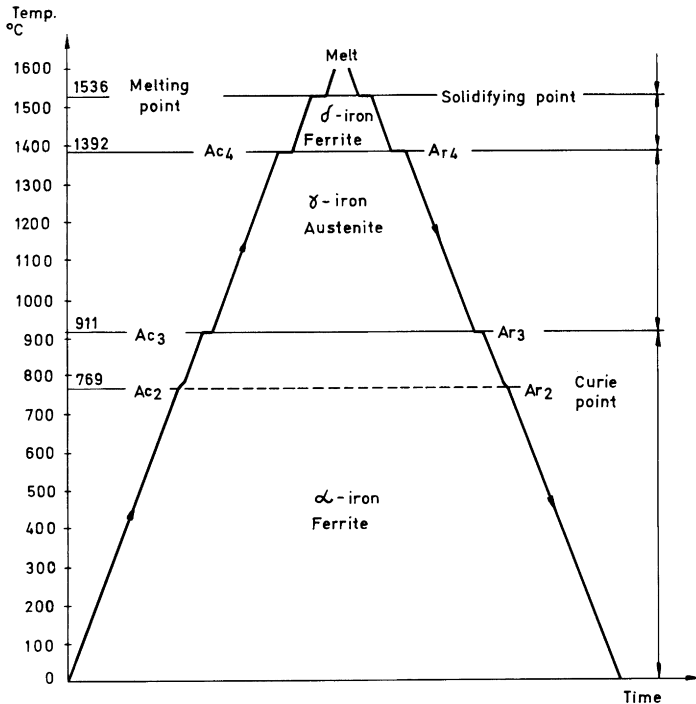


Figure 1.1. Heating and cooling curve for pure iron

Ferrite, besides having an atom at each corner of the unit cell, has another atom at the intersection of the cube body diagonals, i.e. a body-centred cubic lattice (BCC). The length of the unit cube edge or lattice parameter is 2.87 Å at 20 °C (Å = Ångström = 10^{-8} cm). Austenite has a face-centred cubic lattice (FCC), the parameter of which is 3.57 Å (extrapolated to 20 °C). The structure of the unit cells of α -iron and γ -iron respectively may be envisaged as shown in Figure 1.2. The γ -iron unit cell has a larger lattice parameter than the α -iron cell but the former contains more atoms and has a greater density, being 8.14 g/cm³ for γ -iron at 20 °C and 7.87 g/cm³ for α -iron.

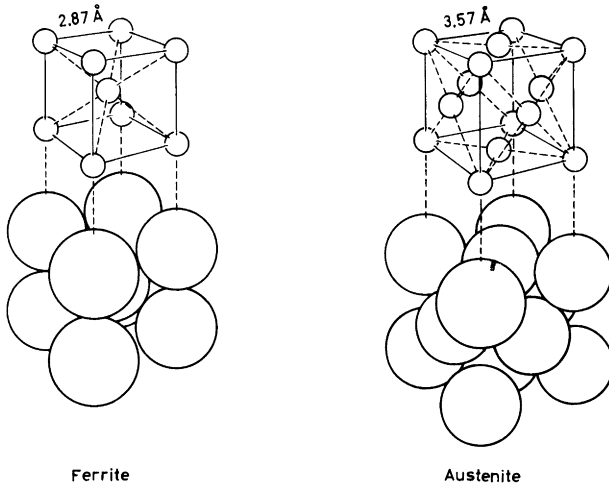


Figure 1.2. The crystal structure of ferrite and austenite

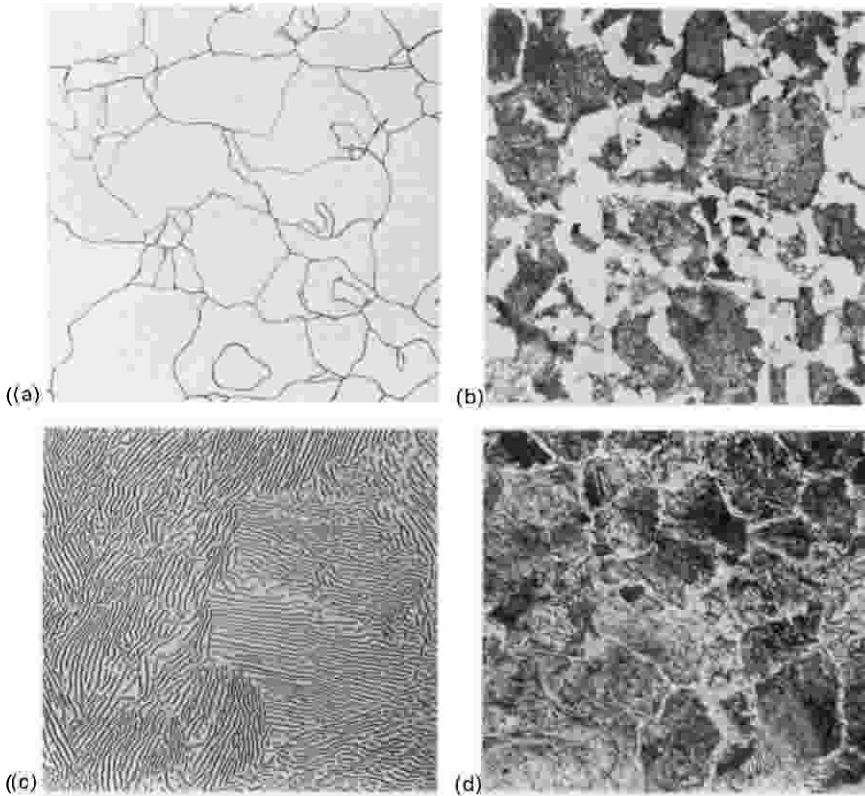


Figure 1.3. Microstructure of carbon steels with varying carbon content: (a) Ferrite 0.0% C. 500 × ; (b) Ferrite + pearlite 0.40% C. 500 × ; (c) Pearlite 0.80% C. 1000 × ; (d) Pearlite + grain boundary cementite 1.4% C. 500 ×

4 FUNDAMENTAL METALLOGRAPHIC CONCEPTS

1.2 THE IRON-CARBON EQUILIBRIUM DIAGRAM

The most important alloying element in steel is carbon. Its presence is largely responsible for the wide range of properties that can be obtained and which make this metal such a highly useful commodity of everyday life. At room temperature the solubility of carbon in α -iron is very low and therefore the carbon atoms are to be found only very infrequently in between the individual iron atoms. Instead the carbon is combined with iron carbide, also called cementite, Fe_3C . The iron carbide may be present as lamellae alternating with lamellae of ferrite, which together form a constituent called pearlite, the mean carbon content of which is 0.80%. The proportion of pearlite in the

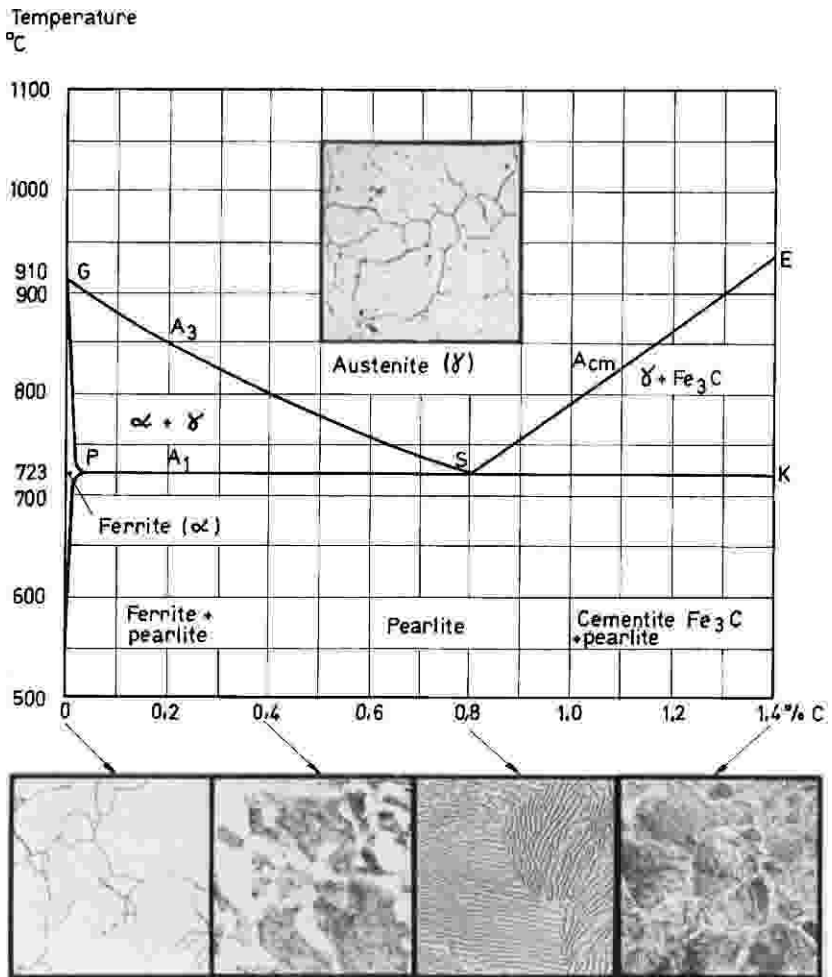


Figure 1.4. The lower left-hand part of the iron-carbon equilibrium diagram

structure increases with the carbon content of the steel up to 0.80%. Carbon in excess of this amount separates as grain-boundary carbides. A steel containing 0.80% carbon is said to be eutectoid (see Figures 1.3a-d).

When iron is alloyed with carbon the transformation will take place within a temperature range which is dependent on the carbon content as shown in the iron-carbon equilibrium phase diagram. Figure 1.4 illustrates various microstructures appropriate to that part of the iron-carbon diagram which applies to steel heat treatment. For the sake of completeness the phase diagram

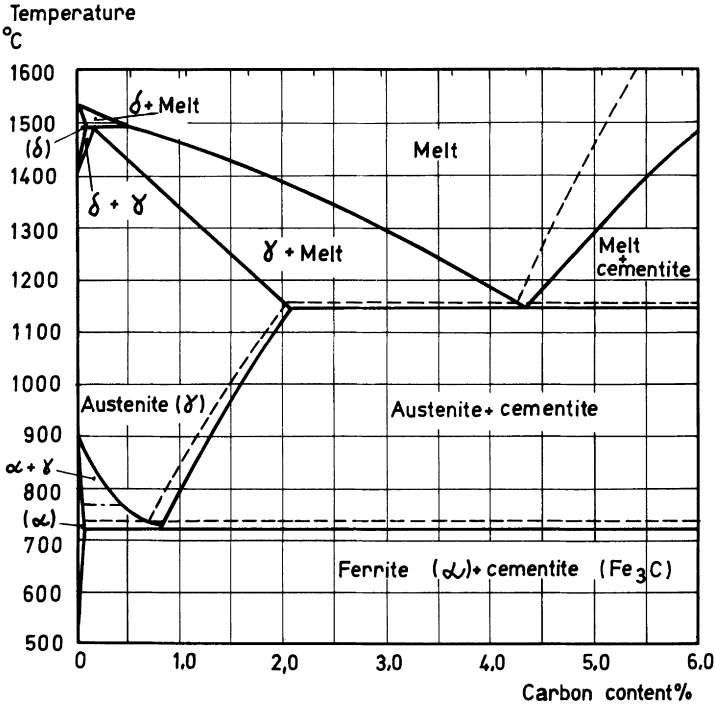


Figure 1.5. The iron-carbon equilibrium diagram:

- the stable Fe-C system;
- the metastable system Fe-Fe₃C

is reproduced as far as 6% carbon in Figure 1.5 where it can be observed that the solubility of carbon is much greater in austenite than in ferrite.

1.2.1 Heating

It was mentioned earlier that α-iron transforms to γ-iron on being heated to 911 °C. This can be seen by looking at the vertical axis of the left-hand part of the diagram in Figure 1.4. In a steel containing 0.80% carbon, i.e. a eutectoid steel, the transformation to austenite takes place at about 723 °C. The temperature at which α-iron, γ-iron and cementite are at equilibrium is

6 FUNDAMENTAL METALLOGRAPHIC CONCEPTS

designated A_1 (line PK in diagram). Steels with less carbon, which are called hypo-eutectoid steels, begin to transform from pearlite to austenite at the same temperature, viz. 723°C . In the equilibrium region between PS and GS there is austenite, formed from pearlite, and unchanged ferrite. The transformation is not complete until a temperature A_3 given by the line GS is reached. Above this line there is only one stable phase, viz. austenite. If the carbon content is more than 0.80% the steel is said to be hyper-eutectoid. In these steels, too, the pearlite transforms into austenite at 723°C but the cementite (iron carbide) does not go into solution completely until the temperature rises above the equilibrium line SE, designated A_{cm} .

Let us for a moment return to the course of events taking place during heating. At 723°C we find that the transformation to austenite begins to take place in steels having more than 0.025% carbon. This means that the atomic configuration changes from ferrite to austenite in which the carbon atoms

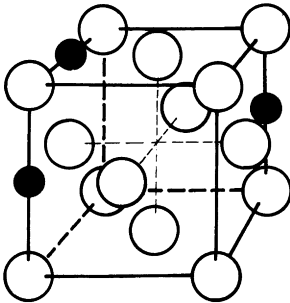


Figure 1.6. Examples of positions of carbon atoms in γ -iron

are more soluble. The positions of carbon atoms in austenite are illustrated in Figure 1.6. At temperatures above G-S-E there is austenite only, all the carbon having been dissolved and evenly distributed throughout the austenite.

1.2.2 Cooling

As the temperature of a fully austenitized eutectoid plain carbon steel is slowly lowered below 723°C the transformation from γ -iron to α -iron begins to take place and as a consequence the carbon is forced out of the lattice and forms cementite. On complete cooling to room temperature the steel has once again its pearlitic structure.

1.3 TIME-TEMPERATURE-TRANSFORMATION

The iron-carbon equilibrium diagram is unquestionably of fundamental importance to heat-treatment processing. However it only describes the situation when equilibrium has been established between the components carbon and iron. In the great majority of heat treatments the time parameter

is one of the determinative factors, the influence of which is shown by so-called time–temperature–transformation diagrams. From these diagrams it is possible to follow the effect of both time and temperature on the progress of transformation.

1.3.1 Heating

The influence of time is best explained by means of the diagrammatic illustrations in *Figures 1.7a–f*. *Figure 1.7a* shows the familiar iron–carbon diagram in which it is seen that a 0.80% carbon steel, on being heated, transforms to austenite at 723 °C. However, the diagram tells us nothing about how long this transformation will take. From *Figure 1.7b*, which applies to a 0.80% carbon steel only, it can be predicted that when the temperature is maintained at 730 °C the transformation will be initiated in about 30 s (logarithmic time scale). If instead the steel is rapidly heated to 750 °C the transformation will begin in 10 s and if heated to 810 °C, in slightly over 1 s, i.e. practically at once on reaching this temperature. The transformation of pearlite to austenite and cementite is completed in about 6 s at 810 °C. If the steel is to be fully austenitic it must be held at this temperature for about 5 h. In actual practice, i.e. when heating for hardening, the cementite is seldom brought into complete solution.

Figures 1.7c and *d* which apply to a 0.45% plain carbon steel show in the same way that at 810 °C, for instance, the transformation from pearlite to austenite starts almost immediately. In about 5 s the pearlite has been transformed and the structure consists of ferrite, austenite and cementite. About 1 min later the carbon has diffused to the ferrite which has thereby been transformed to austenite. Residual particles of cementite remain, however, and it takes about 10 h to dissolve them completely.

On heating a hyper-eutectoid steel containing 1.2% carbon to 810 °C a structure consisting of austenite and cementite is obtained in about 5 s (*Figures 1.7e* and *f*). It is not possible for the cementite to be completely dissolved at this temperature, this is apparent from a perusal of the equilibrium diagram. In order to effect complete solution of the cementite the temperature must be increased to 860 °C at least.

In order to study the rate of solution the steel is heated to a predetermined temperature, and after holding it there for a certain time it is quenched in water thereby ‘freezing’ the pre-existing structure. By this treatment, however, the austenite is transformed to martensite (for a discussion of this see p.15).

The result obtained from such an experiment, applied to a 0.45% carbon steel, is shown in *Figure 1.8*. In all cases the holding time at temperature was 5 min. *Figure 1.8a* shows the original structure which consists of about 50% of ferrite and 50% of pearlite. On being heated to 725 °C for 5 min some of the cementite lamellae are converted to spheroids. This is called spheroidization. A decrease in hardness is a result of this process. There is no transformation (see also *Figure 1.7*). When it is heated to 735 °C (*Figure 1.8c*) the main part of the pearlite is transformed to austenite which, on being quenched, forms martensite. Some ferrite and pearlite remain untransformed. A holding time

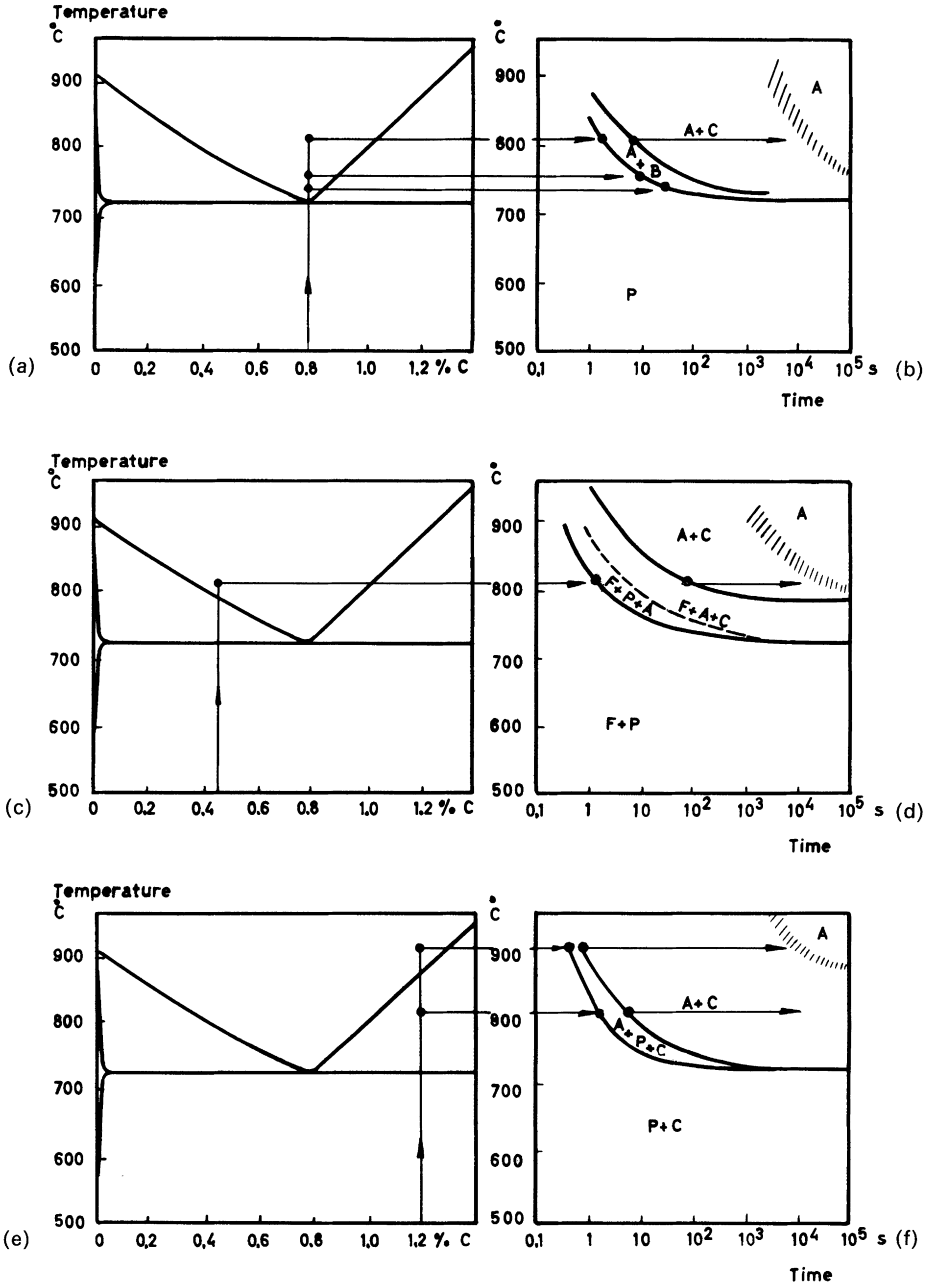


Figure 1.7. Structural transformations on heating steels containing: (a) 0.80% C; (b) 0.80% C; (c) 0.45% C; (d) 0.45% C; (e) 1.2% C; (f) 1.2% C. Schematic representation (after Rose and Strassburg¹)

A = austenite, B = bainite, C = cementite, F = ferrite, P = pearlite

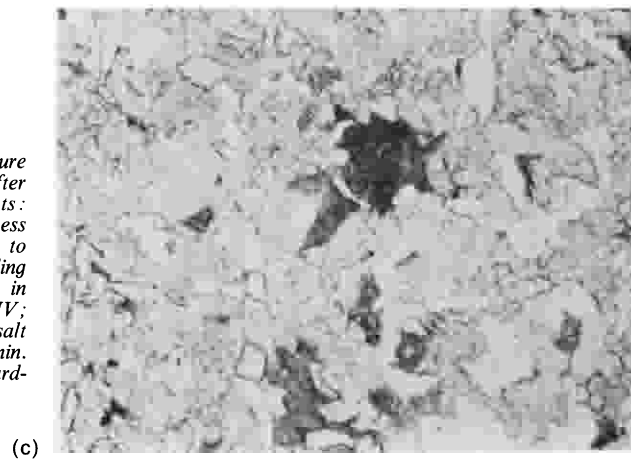
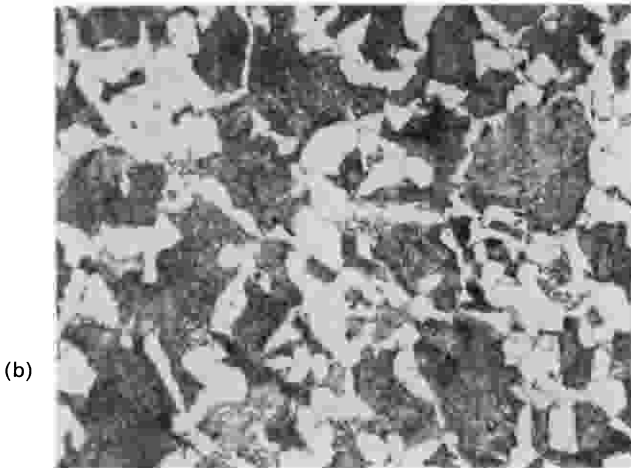
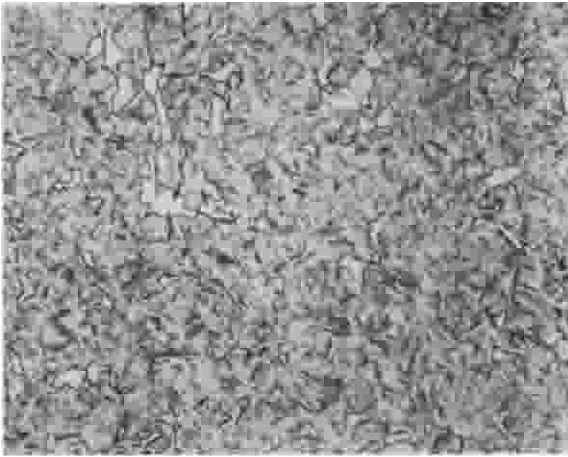
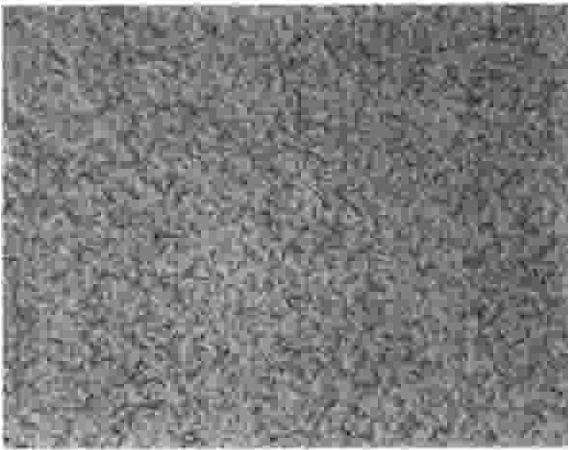


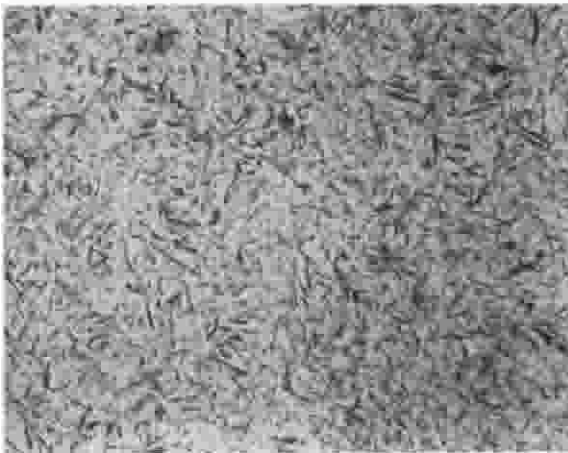
Figure 1.8. Microstructure of a 0.45% C steel after various heat treatments: (a) Untreated, hardness 220 HV; (b) Heated to 725°C in salt bath. Holding time 5 min. Quenched in water. Hardness 215 HV; (c) Heated to 735°C in salt bath. Holding time 5 min. Quenched in water. Hardness 376 HV



(d)



(e)



(f)

Figure 1.8. Microstructure of a 0.45% C steel after various heat treatments: (d) Heated to 750°C in salt bath. Holding time 5 min. Quenched in water. Hardness 662 HV; (e) Heated to 775°C in salt bath. Holding time 5 min. Quenched in water. Hardness 738 HV; (f) Heated to 825°C in salt bath. Holding time 5 min. Quenched in water. Hardness 744 HV

of 5 min at 750 °C (Figure 1.8d) is sufficient to transform all the pearlite but about 5% of the ferrite remains unchanged. However, 5 min at 775 °C is not sufficient to transform all the ferrite, as is apparent in Figure 1.8e which shows traces of this constituent. At 825 °C, on the other hand, all the ferrite has been transformed in 5 min. Cementite, however, is still in evidence, which is in agreement with Figure 1.7.

Varying the rate of heating to the hardening temperature will have an effect on the rate of transformation and dissolution of the constituents. Figure 1.9 shows a continuous-heating diagram for a steel of almost eutectoid

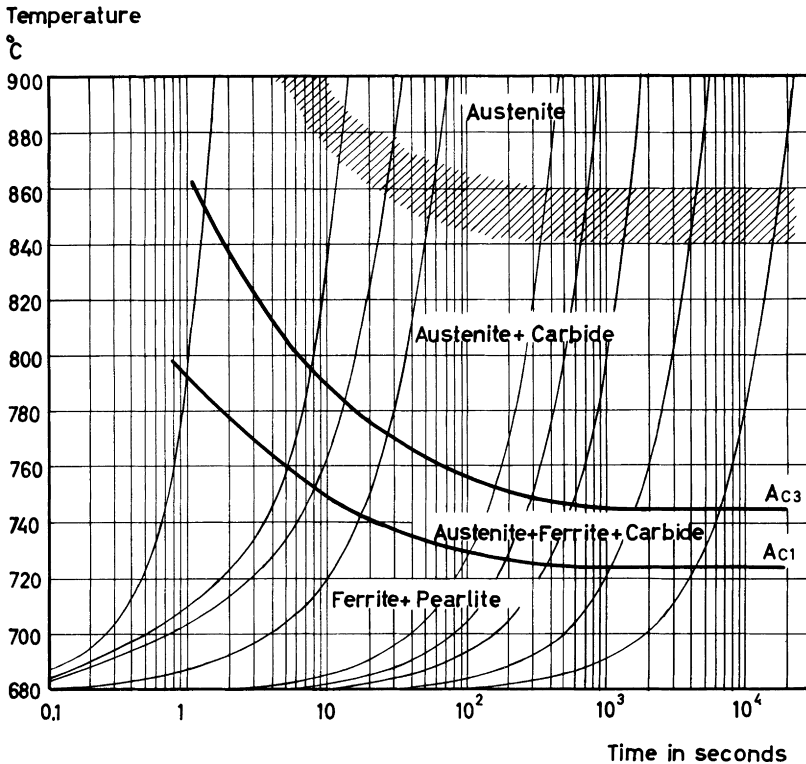


Figure 1.9. Transformation diagram for continuous heating. Dissolution of ferrite and lamellar pearlite in a 0.70% C steel (after Rose and Strassburg¹)

composition and consisting originally of ferrite and pearlite¹. The third curve from the right represents a heating rate of about 3° per minute. The temperature of transformation increases as the rate of heating increases. The temperature for complete solution of the residual carbide was determined dilatometrically (i.e. by change of dimension accompanying phase changes) and differs therefore somewhat from Figure 1.7, the data for which were determined metallographically.

A complete set of continuous-heating curves for various grades of steel would be of great help in the field of practical heat treatment. Since such diagrams are generally not available we must be content with simple

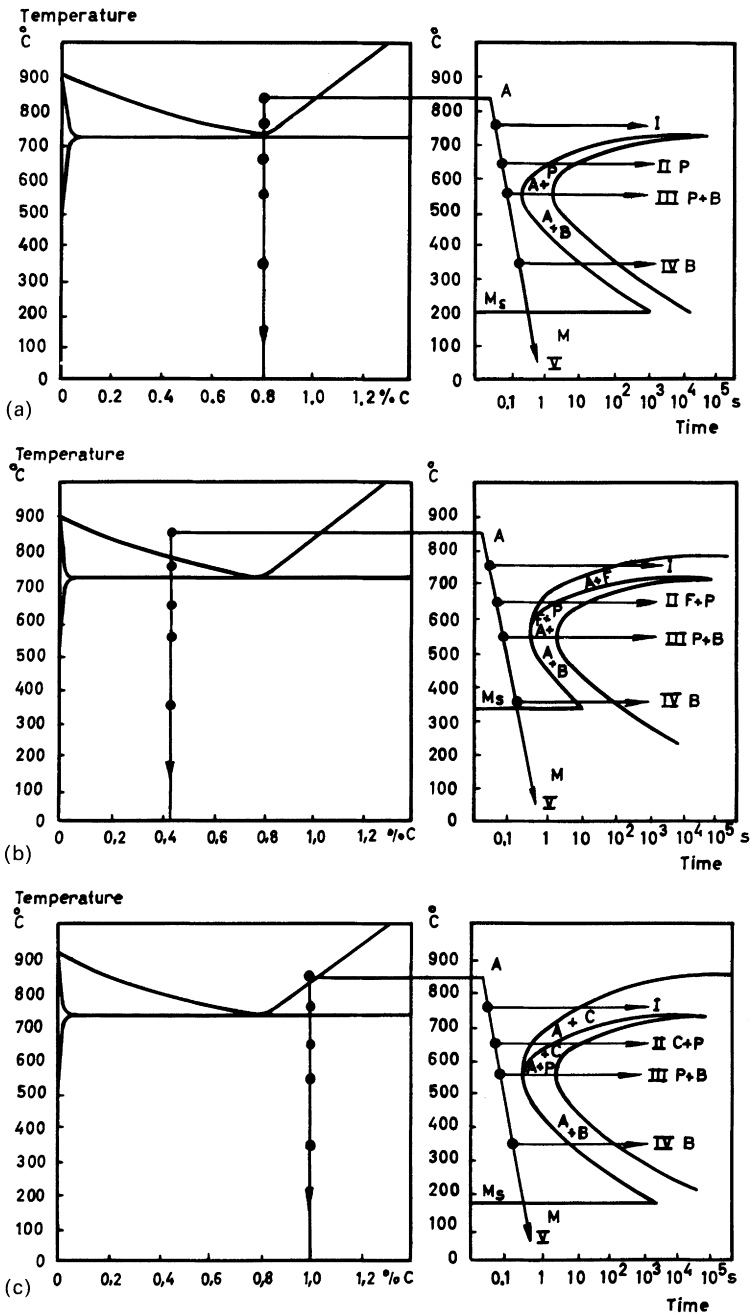


Figure 1.10. Structural transformations resulting from various cooling programmes for steels containing: (a) 0.80% C; (b) 0.45% C; (c) 1.0% C

A = austenite, B = bainite, C = cementite, F = ferrite, P = pearlite, M = martensite, M_s = start of martensite formation

estimations of heating and holding times. However, a commendable achievement in this field has been accomplished by the issuing of *Atlas zur Wärmebehandlung der Stähle*, Volume 3 in 1973.

1.3.2 Cooling

The general appearance of the structure created during cooling is dependent on the temperature of transformation and on the time taken for the transformation to start. As in the case of heating, the iron–carbon equilibrium diagram can tell us nothing about this. In a manner similar to that described above, the transformation of steel at a certain temperature may be investigated by cooling it from the austenitic state to the temperature concerned, letting the transformation take place and then quenching to room temperature. The structure thus obtained is then studied under the microscope.

1.3.3 Formation of pearlite

When a eutectoid steel is cooled from an austenitizing temperature of, say, 850 °C to 750 °C then, according to the iron–carbon equilibrium diagram no transformation will take place. If the temperature is lowered to 650 °C pearlite will start to form after 1 s and the transformation will be completed in 10 s (see curve II in *Figure 1.10a*). As the temperature of pearlite formation is lowered the pearlite lamellae become increasingly finer and the whole structure becomes harder. If we allow the transformation of the hypoeutectoid steel in *Figure 1.10b* to take place at 750 °C, only ferrite separates and a state of equilibrium is established between ferrite and austenite (curve I). If the transformation takes place at 650 °C ferrite separates first followed after a short interval by pearlite. Similarly, in the case of the hyper-eutectoid steel, *Figure 1.10c*, cementite separates first followed by pearlite.

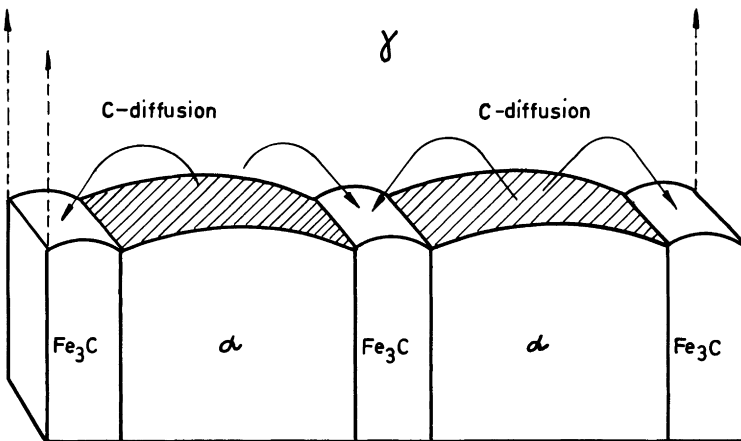


Figure 1.11. Schematic representation of pearlite growth (after Hillert²)

14 FUNDAMENTAL METALLOGRAPHIC CONCEPTS

Pearlite formation is initiated at the austenite grain boundaries or at some other disarray in the austenite grains. The process has been studied in detail by Hillert² who found that pearlite formation can be initiated on either ferrite or cementite and that pearlite growth proceeds by branching. Platelets of cementite and ferrite grow in juxtaposition since carbon transport from the austenite to the edges of the cementite platelets results in a simultaneous carbon impoverishment of the edges of the ferrite platelets. *Figure 1.11* shows how pearlite grows according to this model.

1.3.4 Formation of bainite

At temperatures below about 550 °C another constituent, bainite, starts to separate along with the pearlite. Its formation is assumed to be initiated on ferrite nuclei which grow as platelets from the grain boundaries. The carbon content of the surrounding austenite increases continuously and when it has reached a limiting value platelets of cementite form in juxtaposition with platelets of ferrite.

As the temperature falls bainite begins to form inside the grains as well; at the same time the mode of formation changes. In the metallurgical microscope it may be difficult to differentiate bainite from other constituents since bainite alters its appearance according to its temperature of formation and the composition of the steel. *Figure 1.12* shows bainite in a chrome–manganese steel.

Depending on the temperature of formation of bainite it is classified as



Figure 1.12. Bainite 500 ×

upper or lower bainite. The mode of formation of the various types of bainite as well as their properties have been described by Pickering³. For the present purpose it is sufficient to indicate that upper bainite is relatively brittle and lower bainite is tough.

1.3.5 Formation of martensite

Referring to *Figures 1.10a-c*, if cooling takes place as represented by curve V, i.e. very rapidly, austenite will start to transform to ferrite on reaching line M_s . As the cooling continues below M_s there is very little carbon migration while the austenite is transforming. Thus, the carbon atoms remain in solid solution in the α -iron. Since the space available for the carbon atoms is less in α -iron than in γ -iron the carbon atoms will expand the lattice. The resulting state of stress increases the hardness of the steel. We say that the steel has been *hardened*. The new constituent, called martensite, is a super-saturated solution of carbon in α -iron.

The mechanism of martensite formation is the subject of considerable controversy and several theories have been advanced. *Figure 1.13* illustrates a simple model of how we can picture the transformation of γ -iron to α -iron

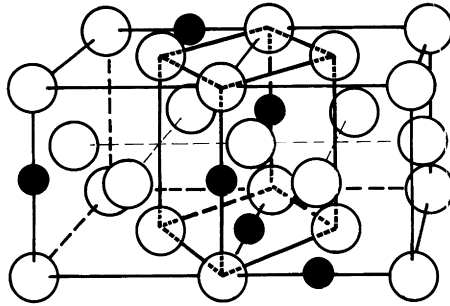


Figure 1.13. Simple model for the transformation of austenite (γ) to martensite (α)

during martensite formation. The carbon atoms situated on the edges of the martensite unit cube cause the unit cell to increase in one direction, which results in a tetragonal lattice. Even in the case of high-carbon steels only a very small fraction of the number of possible lattice sites are occupied by carbon atoms. The volume of the martensite increases with increasing carbon content.

From the transformation diagrams it will be seen that the formation of pearlite and bainite progresses with time whereas that of martensite does not. Each temperature below M_s corresponds to a definite proportion of martensite but the amount actually formed depends on the grade of steel, the conditions of the austenitizing treatment and the rate of cooling on quenching for hardening. As the temperature falls it is possible to follow visually the martensite transformation in a so-called hot-stage microscope. *Figures 1.14a-f* show the progress of martensite formation. It starts at 220°C and at 175°C the main part of the austenite has been transformed to martensite.