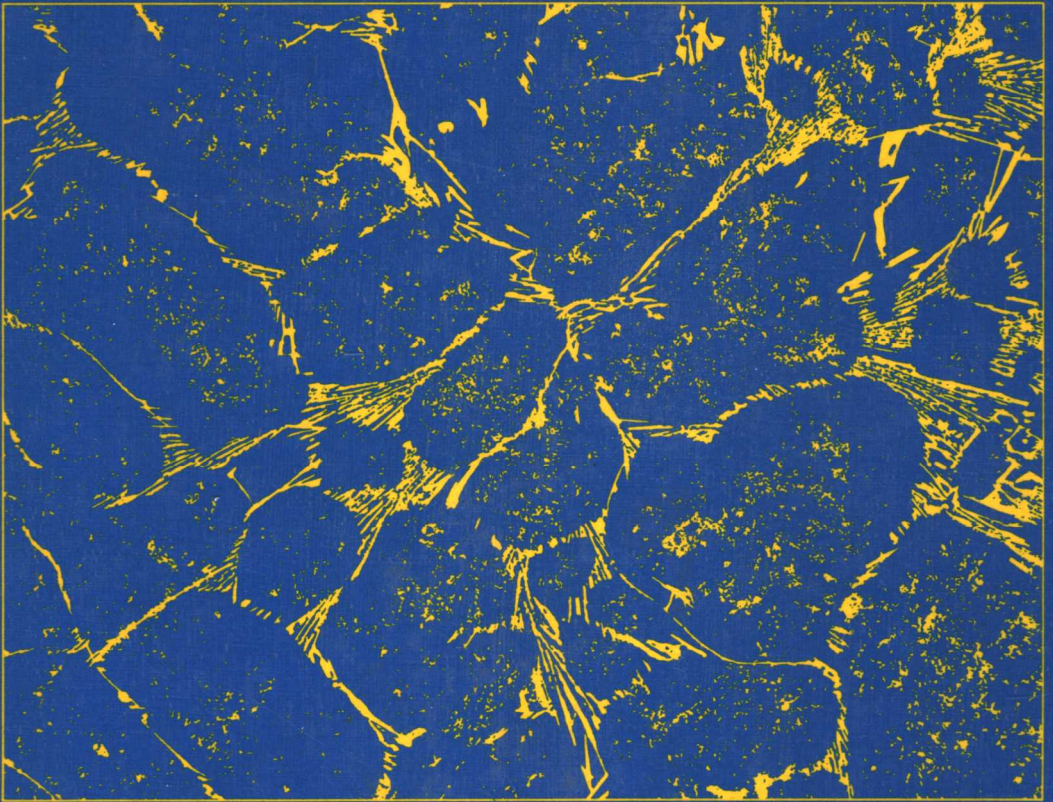# High Speed Steels

Geoffrey Hoyle

Butterworths

High Speed Steels

G. Hoyle, BSc, FIM, CEng
Metallurgist Consultant

Foreword

I feel pleased and honoured to have been invited to write this foreword to *High Speed Steels* by Geoffrey Hoyle. Geoffrey and I were both students together many years ago at Leeds University where we came under the influence of the late Professor Archie Preece. Preece taught us to look for the origins of microstructures in relation to alloy composition, casting conditions and the subsequent working and heat treatments. But above all, Preece got us enthusiastic about the subject of metallurgy and its applications.

The present book shows how the metallurgy of high speed steels has advanced since Mushet's original discovery some 120 years ago of the effects of tungsten additions to steel and brings together much new information particularly in relation to surface treatments. Despite predictions about the substitution of high speed steels by ceramics and cermets, frequently linked to dire warnings about world shortages of tungsten, these traditional materials continue to be used. With the discovery of the extent of Hemerdon tungsten deposits in South-West England, and the opening of new mines in the Western World even the strategic arguments against using high speed steels have disappeared. Therefore, this book should not be looked upon as an historical treatise but rather as providing a background to a class of material with a long working life ahead of it.

Geoffrey Hoyle has shown that he has learnt some valuable lessons from his earlier mentor, not the least being an enthusiasm for his chosen subject.

Jack Nutting, F.Eng.
Leeds University

Preface

High speed steels have been known for about a century, during which time there have been many developments to keep pace with increasing demands on properties and with advances in basic metallurgical understanding. So far, it has been possible to meet all challenges and, after a period of uncertainty in the early 1980s, there appears to be a resurgence in the importance of the material. At a recent conference[159] one speaker commented that, contrary to the opinions of some pessimists, the obituary to high speed steel was definitely NOT being written.

In a field where the tonnage produced is low but the cost is high, it is perhaps natural that the material has not received as much attention from research workers and authors as have some of the more widely used materials and books on the subject have been few. The present work is an attempt to summarize the basic metallurgical aspects of the subject as they are known in the mid-1980s, covering the developments that have taken place during almost 50 years to give the high speed steel industry a scientific base.

Special attention has been given to the subject of surface treatment which, although not specifically related to high speed steels, is an important factor in upgrading the properties of the material to meet competition from other materials.

The book is intended to discuss the background metallurgy rather than to provide lists of properties and other information that is readily available from manufacturers and in the appropriate handbooks. I have endeavoured to include as much material as possible within the text length agreed with the publishers, but inevitably there are some omissions for which I can only apologize.

Acknowledgements

I am most grateful to those who have helped in the preparation of this book by discussion, provision of information and material, granting permission for reproduction of copyright material or in any other way. As the literature cited and the illustrations used cover a long timespan — an indication of the way in which some features have remained unaltered for many years whilst there have been rapid changes in other aspects — I have not been able to contact all the copyright holders but in most cases have received assurances that no objections would be raised. In these cases, I hope that my acknowledgement will be accepted along with an unreserved apology where this would be applicable.

I am particularly grateful to Dr J. and Mrs A. Rodic (now at the Slovenske železarne Institute of Metallurgy, Ljubljana) for personal assistance and provision of unpublished material for illustration.

The following acknowledgements are made for figures and tables.

Osprey Ltd.: *Figures 3.14, 3.15.*

Sprayforming Developments Ltd.: *Figure 3.17.*

Zelezarne Ravne: *Figures 3.14, 4.15, 4.19–4.24, 7.1, 7.5–7.7, 7.9, 8.2–8.11, 8.19, 8.20–8.22.*

Japan Special Steel: *Figure 3.21.*

GFM: *Figure 3.22.*

VEW: *Figures 4.12, 4.13, 4.18, 4.44, 6.1, 8.42, 8.48, 10.10, 10.14.*

Verlag. Stahleisen: *Figures 4.25, 7.1, 7.2, 7.12.*

Dr E. M. Trent: *Figures 6.1, 6.3–6.5, 8.12, 8.13.*

Plansee: *Figures 6.1, 6.6.*

Multi-Arc Corporation: *Figure 9.19.*

Dr A. B. Smith: *Figures 6.2, 8.7, 8.8, 9.14, 9.15, 9.20–9.22, 10.4, 10.5, 10.7; Table 10.2.*

Dr A. S. Wronski: *Figures 8.30, 8.40.*

Arch. Eisenhuttenwesen: *Figure 8.48.*

British Heat Treatments: *Figures 9.1, 9.3, 9.11, 9.12.*

Heat Treatment of Metals: Figures 9.4, 9.9, 9.13.

AERE: *Figure 9.10.*

Mazda Motor Corporation: *Figure 9.2.*

Balzers A. G.: *Figures 9.18, 10.9, 10.15, 10.16.*

T. I. Abar: *Figures 9.16, 9.17, 10.11.*

Powdrex Ltd: *Figure 10.1.*

Contents

Introduction

High speed steel takes its name from its capacity to retain a high level of hardness when cutting metals (and other materials) at high speed. It is also appropriately named in view of more recent applications such as bearings for aircraft jet engines and for space-vehicle components. In either event, the important factor is that the steel can be hardened to a level of up to 1000HV or 65–70HRC, and that no appreciable softening takes place until temperatures in the region of 600°C are reached.

High speed steels have been known in some form for over a century. The origin seems to be the accidental discovery by Robert F. Mushet (whose name is still used by a well-known toolmaker) in 1868 that a steel containing tungsten became hard when air cooled from a temperature from which most steels required water quenching for hardening. The full capabilities of the steel were not, however, realized until after experiments by Maunsel and White, of Bethlehem Steel works, dating from 1898, revealed the potentiality of hardening from a very high temperature, and it was even later that the benefits of secondary hardening by tempering at temperatures in the region of 550°C were realized. The first real high speed steel as defined by modern standards was the 18–4–1 composition developed by the Crucible Steel Company. This steel, now generally known by its specification number, T1 (or BT1 in British specification terminology, or S 18–0–1 in West Germany), contains 18% tungsten, with 4% chromium and 1% vanadium, and about 0.7% carbon. This steel remained popular until the 1950s, when it was overtaken by a tungsten–molybdenum steel, M2 (or BM2 or S 6–5–2), in which one-third of the tungsten in T1 was replaced by 5% molybdenum and the vanadium content raised to 2% and the carbon to 0.85%. There are now many different varieties of high speed steel, which will be discussed in a later chapter, but for a discussion of the principles in the production and heat treatment and examination of the materials, T1 and M2 will be taken as appropriate. T1 is included in the discussion at this stage because its constitution is rather simpler than that of M2, which includes an extra element, molybdenum. The more complex steels contain elements such as cobalt, and experimental steels have been based on tantalum and niobium. The composition of the three basic high speed steels is given in *Table 1.1:* a more complete list of standards is given in *Table A1,* and will be required for reference, but it should be stated here that the trend is always towards a reduction and rationalization of the number of alloys on the market, in the interests of economy of supply and standardization of heat treatment, etc.

TABLE 1.1 Nominal composition (wt %) of the three basic high speed steels

Specification	C	W	Mo	Cr	V
T1	0.75	18		4	1
M1	0.8	2	8	4	1
M2	0.85	6	5	4	2

The main objective in high speed steel technology and production is to produce tools that are satisfactory in performance and can be produced at a reasonable cost. Technology thus varies according to the application, and the choice of material may vary from time to time according to the cost of raw materials, which fluctuates considerably and may favour different elements at different times. Thus the ultimate product is a compromise between the needs of the manufacturer and those of the consumer.

Production of the conventional high speed steel involves melting, casting, hot-working and heat treatment, as for other steels. In recent years, however, there have
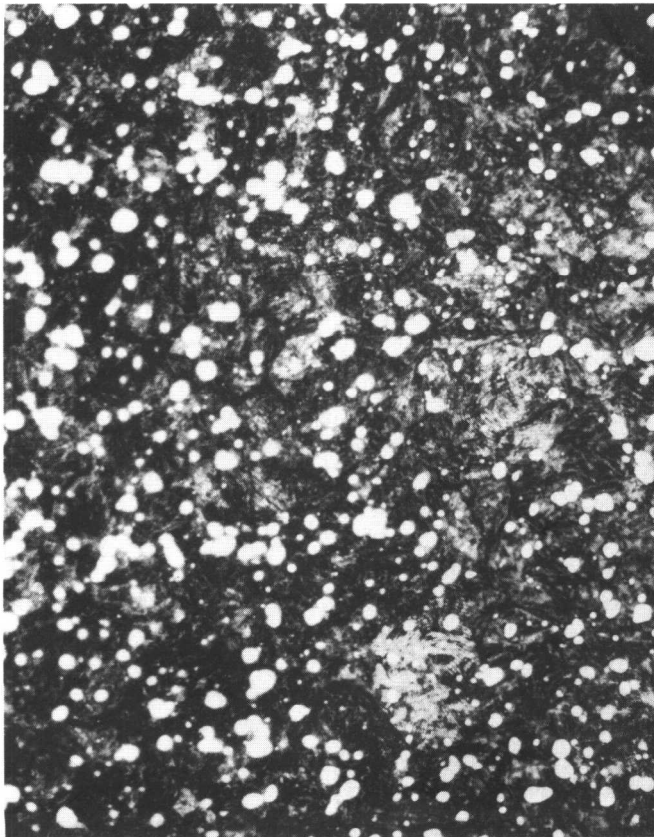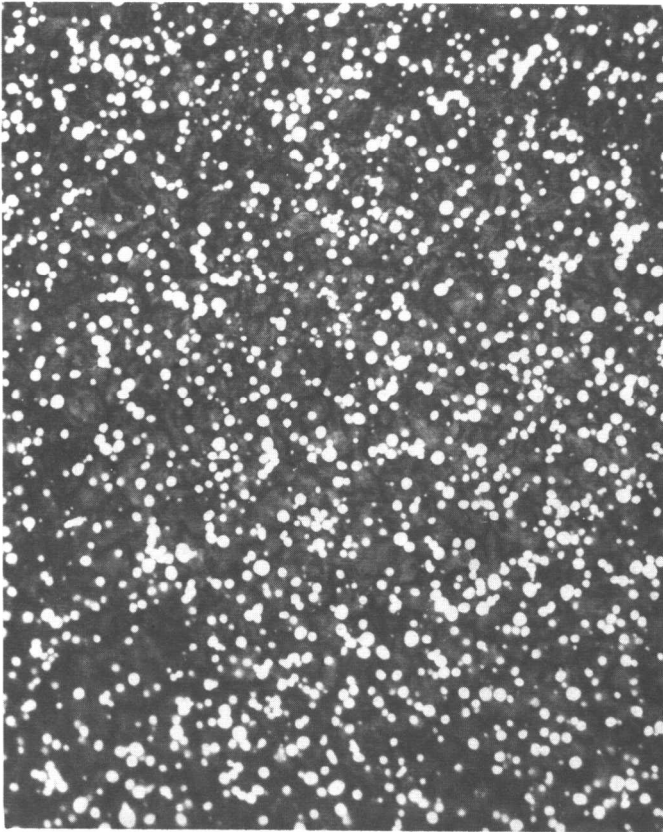

Figure 1.1 Microstructure of a typical high speed steel specimen, conventionally produced, hardened and tempered. Transverse structure (× 1000). (Courtesy SKF & Dormer.)

been important developments in the use of powder metallurgy techniques, which can overcome some of the problems inherent in the normal production route. The powder method will not be treated as an individual topic, but will be discussed alongside the other techniques where appropriate.

High speed steels are characterized by a very long freezing range, which is conducive to segregation, and invariably the as-cast structure contains eutectic which is an essential feature and yet is at the root of most of the problems encountered. The rules of solidification are now being applied to high speed steel production, particularly in the case of special techniques such as electroslag remelting that can ensure improved structure by controlling solidification rate, with attendant improvements.

The ingot product is subject to hot-working, which may be of the order of 95% or more, to give a structure containing a fine dispersion of carbide particles, the product of the eutectic phase after breaking the cellular network down, in an alloyed matrix. A typical structure is shown in *Figure 1.1 (see Figure 3.17* for longitudinal structure).

In the case of powder metallurgy, the segregation pattern is minimized, and a more uniform distribution of carbides is possible *(Figure 1.2).*

Figure 1.2 Microstructure of typical high speed steel produced by powder methods, hardened and tempered ($\times$ 1000). (Courtesy SKF & Dormer.)

Heat treatment of high speed steels is a complex procedure. Austenitizing is usually at a temperature very close to the solidus point, for a short time, so as to take as much carbide as possible into solution. After quenching there is a considerable amount of retained austenite, which is transformed on cooling from the first tempering operation. A second (perhaps a third) tempering operation is needed to temper any fresh martensite so formed. The important thing about tempering is that there is a secondary hardening effect as the tempering temperature rises above 350°C, to give a peak hardness after tempering in the range 525–575°C, depending on the alloy. The shape of a typical tempering curve is shown in *Figure 1.3.*
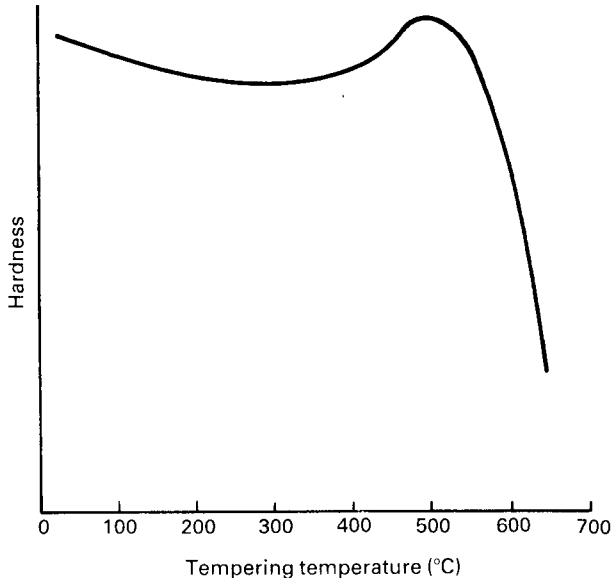
Figure 1.3 Typical tempering curve for high speed steel (schematic).

The attainment of maximum hardness levels of the order of 1000HV (70HRC) is possible, and as seen from the shape of the tempering curve the fall off in hardness does not become rapid until temperatures of the order of 600°C or higher are reached. This is the basis of the hot hardness or red hardness that are major features of the steels.

The surface hardness of tools can be increased by special treatments, some of which have been known and used for many years. An important development, the practical application of which has been recognized in the 1980s, is the deposition of special hard coatings on tools by chemical (CVD) or physical (PVD) methods. Titanium nitride coatings have been found to increase the life of many cutting tools by a factor of between 3 and 10 according to application, and to give properties that enable the maximum potential of the high speed steel to be realized, in the range where carbide tools have made some inroad. The ranges of operation of various tool materials are shown in *Figure 1.4.*

The properties required of a high speed steel vary according to the application involved. Materials of the high hardness required are not, of course, characterized by
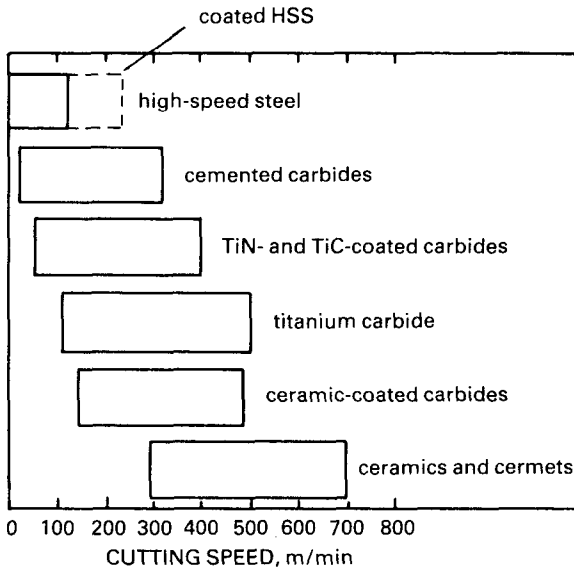
Figure 1.4 Range of operation of various cutting materials when turning carbon steel. (Modified from reference 1.)

extreme toughness, and there is a need for compromise between strength (hardness) and toughness in different degrees. Many different testing procedures are possible, but the choice is normally restricted to bend or impact tests, with fracture toughness measurements to complete the picture: no single test can completely characterize the materials.

Most of the applications of high speed steels are concerned with cutting, and in this context it is necessary to consider the mechanisms and stresses involved. Unfortunately, knowledge on this subject is not complete, but information that is available can be used in selection procedures. Although outside the scope of a monograph on high speed steels, some discussion of the mechanisms in cutting and wear is inevitable; this will be restricted to the minimum. It is essential to remember that the performance of a high speed steel tool is not merely a feature of the material itself and its metallurgical characteristics, but is dependent on the material being cut, the speed of cutting, the lubrication conditions, the nature of the machine tool and the type of cutting (continuous or intermittent).

Besides cutting, high speed steels are used for other purposes such as cold forming tools, or bearings, each of which has its own special requirements.

Constitution

Before discussing the manufacture of high speed steels in detail, it is desirable to look closely at the constitution and mode of solidification of the alloys, so that a better understanding may be gained of the processing methods used.

The generic term 'high speed steel' covers a wide range of compositions, which will be discussed in detail in Chapter 5. To examine the constitution and general behaviour of the materials, most of these steels can initially be considered as being equivalent to a ternary alloy with about 21–25% tungsten, 0.7–1.5% carbon, and the balance iron. This is not, of course, quite accurate, as there is also 4% chromium present almost without exception, with vanadium varying between 1% and 5%. Cobalt is an optional extra, and molybdenum frequently replaces part or all of the tungsten. Thus at best the system is of 5 components (neglecting the minor elements such as manganese, silicon etc). 'Tungsten equivalent' values are attributed to the alloying elements to facilitate treatment on the ternary scale. In the case of molybdenum this is fairly straightforward, as it behaves in a very similar manner to tungsten and is more or less interchangeable on an atomic basis, 1 wt% molybdenum having the same effect as 2% tungsten. In other cases the situation is less clear, as the elements differ in regard to their ferrite- or austenite- forming capacity and their affinity for carbon and the carbides they form.

The simplest alloy in common use, and which was for many years the best documented, is the 18–4–1 steel (usually referred to as T1) developed by the Crucible Steel Company in 1904 and which held precedence for half a century before being supplanted by its rival 6–5–2 or M2 steel which is more complex but in many ways easier to handle. The compositions of the two are given in *Table 1.1*, together with that of M1, in which all of the tungsten in T1 is replaced by molybdenum.

In the molten state, high speed steel may be considered to be reasonably homogeneous (although it is possible for some carbides to remain out of solution during melting), but once solidification has started the material never again assumes a single-phase condition. In the solidified material, the important constituents are the matrix, which is treated as a normal alloy steel hardenable by heat treatment to a high hardness level, and the carbides which are always present in an undissolved condition and which impart the wear-resistant properties to the steel. The structure of as-cast high speed steel *(Figure 2.1)*, which is relevant to the production process, is vastly different to that of the material in the condition usually accepted as normal for the production of tools *(Figure 1.1)*.
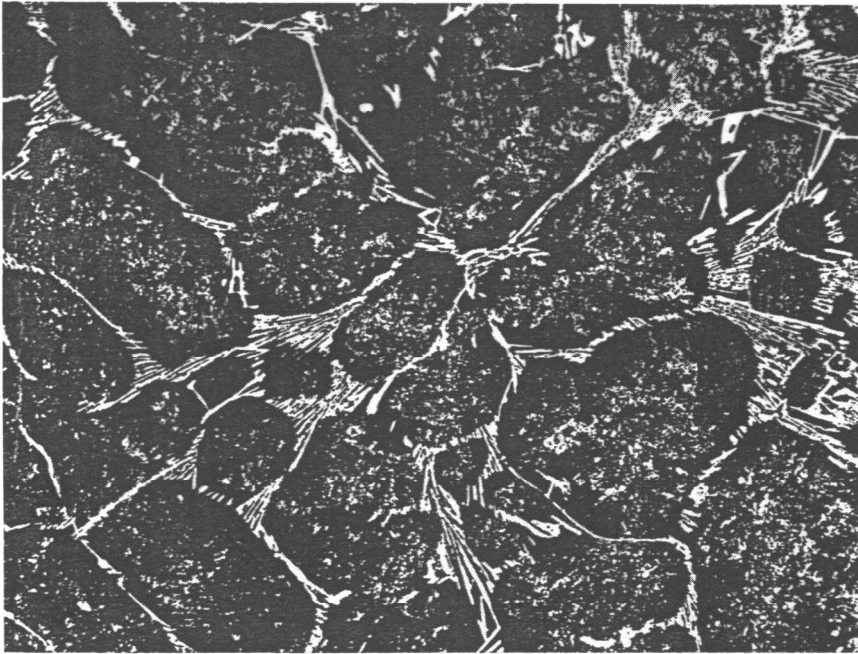
6

Figure 2.1 As-cast structure of M2 high speed steel (*see Figure 3.3* for T1 steel) × 100.

It is therefore necessary to consider the two separately, with discussion of how one is transformed to the other.

2.1 **Constitution**

Because of the complexity of the materials, it is difficult if not impossible accurately to represent the constitution in a two-dimensional diagram. However, by ascribing tungsten equivalent values to elements such as Mo, Cr, V, as discussed in the previous section, it is possible to gain a reasonably accurate impression of the behaviour of the steels by reference to the ternary Fe–W–C system, which has been fairly well documented. Taking the general case of the Fe–M–C system, where M represents W, Mo, Cr or V, i.e. all ferrite-formers, Kuo[2] produced a set of vertical sections from this system at various concentrations of M *(Figure 2.2)*. As the concentration of M increases, the single-phase austenite field present in low alloy steels shrinks rapidly and is absent at the concentration levels usually encountered in high speed steels.

For the representation of tungsten high-speed steels, Kuo[3] made a further refinement and produced a binary section of the quaternary Fe–W–Cr–C system at 18% W and 4% Cr. This diagram, modified slightly by Goldschmidt *(Figure 2.3),* is widely accepted as being the best available representation for the T1 steel (18–4–1) which was popular during the first half of the twentieth century. As this is no longer a ternary system, the peritectic reaction does not take place at a fixed temperature and
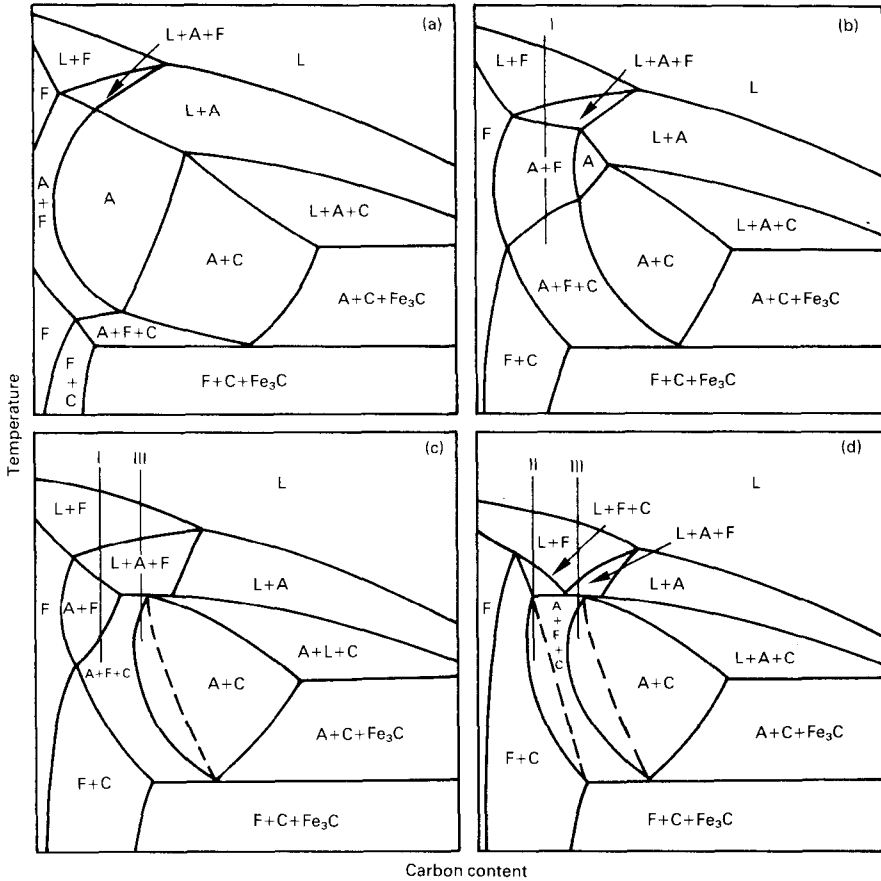
Figure 2.2 Vertical sections through Fe–M–C system at increasing concentrations of M (schematic). M= W, Mo, Cr, or V. (Reproduced from reference 2, by kind permission of authors and publishers.)

a four-phase field is introduced into the diagram. This diagram may be used as a basis for discussion of the reactions taking place during the solidification of most high speed steels, at least for practical purposes. Minor differences will be discussed later, with particular reference to the molybdenum steels.

In *Figure 2.3* the normal range of carbon content for T1 lies between the points *i* and *j*. Thus if equilibrium conditions prevail during solidification, the reactions would be expected to occur in the order:

$$L \rightarrow L+F$$
$$L+F \rightarrow L+F+A$$
$$L+F+A \rightarrow L+F+A+C$$
$$L+A+F+C \rightarrow L+A+C$$
$$L+A+C \rightarrow A+C$$
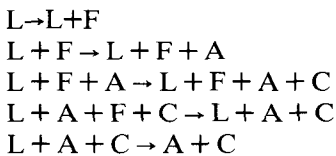
Where L = liquid, A = austenite, F = ferrite, C = carbide (usually M_6C type, discussed in Section 2.2).