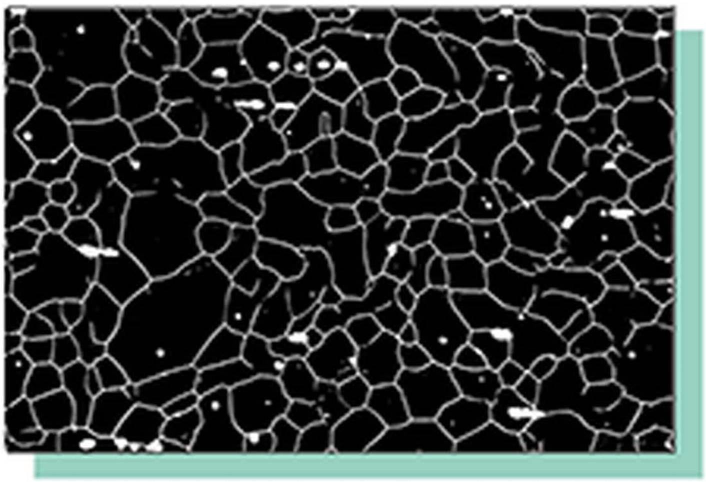
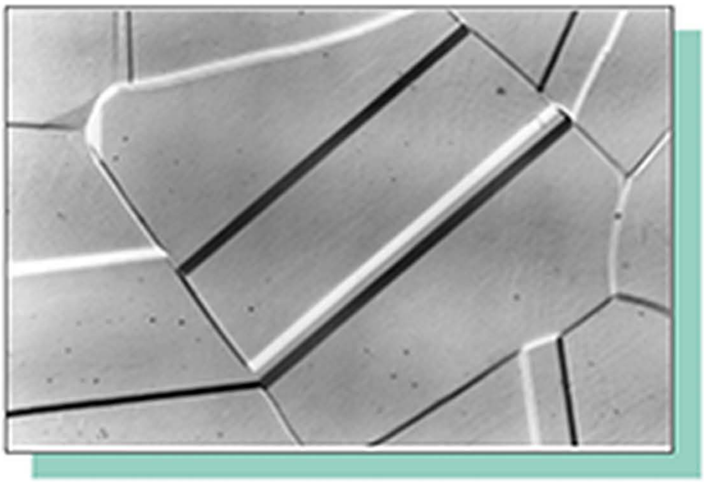
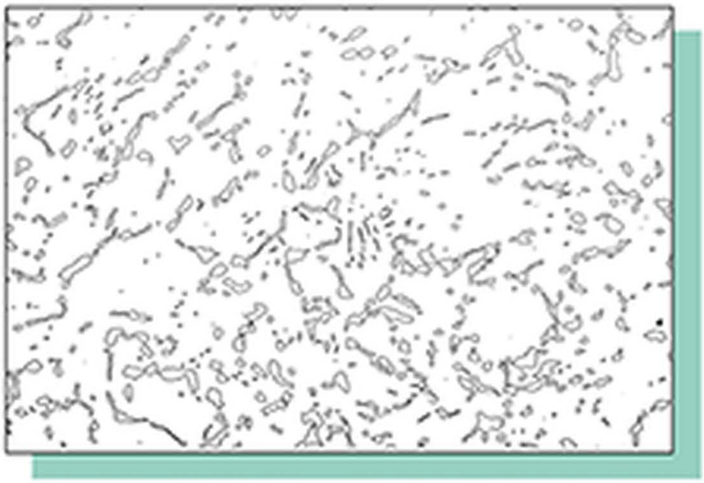
Metallographer's Guide

Practices and Procedures for Irons and Steels







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Metallographer's Guide

Practices and Procedures for Irons and Steels

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Comments, criticisms, and suggestions are invited, and should be forwarded to ASM International.

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Micrographs on cover:

Top, left: Annealed AISI/SAE 1005 steel showing equiaxed ferrite grains photographed using dark field illumination. Marshall's etch. 200×

Top, right: Annealing twins in AISI 347H austenitic stainless steel photographed using differential interference contrast (Nomarski). Electrolytically etched in 60% nitric acid in water. 5 volts, stainless steel cathode. 500×

Bottom, left: Partially spheroidized AISI/SAE 1060 steel photographed using bright field illumination. 4% picral etch. 500×

Bottom, right: Lath martensite in austenitized and quenched AISI/SAE 1040 steel photographed using bright field illumination. Etched in 2% nital. 500×

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To Joan and Sandy for their enduring patience and encouragement.

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Contents

Preface

This guide was prepared not only for the beginning metallographer but also for the experienced metallographer who may be looking for alternatives and new approaches to metallographic practice. For the beginning metallographer, little or no knowledge of steels and cast irons is necessary since the first three chapters provide the basic information needed to understand the various types of steels and cast irons available in the commercial world. These chapters also provide examples of the multitude of microstructures that the metallographer will encounter, how these microstructures are created, and how they can be altered by heat treatment and other means. Some metallographers may be working in a small laboratory where no metallurgical support is available. The authors feel very strongly that to be effective, the metallographer must understand as much as possible about the metallurgy of the material he or she is preparing. Without this knowledge, the metallographer can offer little interpretation of the microstructure he or she develops even after applying the best metallographic practices. Also, without a proper background in recognizing metallographic constituents, he or she may produce an artifact through improper specimen preparation that will lead to a totally inappropriate result. Thus, it is important that the metallographer read the first three chapters to obtain a basic understanding of steel microstructures before proceeding to the metallographic techniques chapters.

As part of this guide, the authors felt that a metallographer should know some of the history of metallography. In this new century, we have come a long way from the early days of Sorby and Widmanstätten who pioneered what we now know as metallography of steels and cast irons a century and a half ago. Chapter 4 gives a brief history of these early metallographers and defines the identity of a metallographer by comparing the vast amount of information gained from a metallographic analysis to that produced from a chemical analysis. The chapter also describes the types of things that a metallographer will encounter in a typical workday in a large metallographic laboratory in the research department of a large steel company and a small metallography laboratory associated with an iron foundry. Actual metallographic tasks in both situations are described in detail. Chapter 6 discusses some of the tools that are available beyond the typical metallographic laboratory. In today's world, there has been an explosion in technology to aid the metallographer. Not only can one reveal the microstructural constituents in a steel or cast iron, but also one can determine the chemical analysis of each constituent even on a nanometer scale. To be effective, the metallographer must be familiar with the capabilities of these modern-day instruments.

Since this guide concentrates on light (optical) metallography, Chapter 5 has been added to describe in detail how a metallurgical microscope works. This is the instrument located in all metallographic laboratories. The metallographer must have an intimate knowledge of the microscope to use it properly. An understanding of the different types of oculars (eyepieces) and objectives is important so that the microstructure can be revealed in its truest form. Knowledge of the various types of illumination (bright field, dark field, interference contrast, etc.) is important to enhance the image of the microstructural features. The metallographer also must know how to maintain and clean the microscope to keep it in the best condition possible.

Specimen preparation procedures were saved for Chapters 7 and 8. The procedures presented in this guide have proven to work effectively to prepare the specimen. However, the authors recognize that other procedures also can work as effectively. This book guides the metallographer through the specimen preparation procedures in a step-by-step manner. Various options are offered, and preferred methods are described in detail. The authors provide a basic understanding of how and why the methods work. As the metallographer becomes more experienced, he or she may develop his or her own adaptations of the procedures presented here. This guide will get the metallographer started with a sound procedure that works.

A unique feature of this guide is a separate and complete index of the various steels and cast irons used as examples throughout the book. The index makes the hundreds of micrographs essentially an Atlas of Microstructures, and it precedes Chapter 1.

Although this book is for the novice metallographer, an experienced metallographer may find it useful in that dozens of special metallographic tips are scattered through the chapters on specimen preparation and the art of revealing microstructure. This guide could be used as a university or technical school text to accompany the teaching of a laboratory course in metallography.

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CHAPTER 1

Introduction to Steels and Cast Irons

STEELS AND CAST IRONS are basically alloys of iron and various other elements in the periodic table. The vast majority of steels and all cast irons contain carbon as a principal alloying element. As a general definition, a steel is an alloy of iron, carbon (under 2% C), and other alloying elements that is capable of being hot and/or cold deformed into various shapes. A cast iron, on the other hand, is an alloy of iron, carbon (over 2% C), and other elements and is not normally capable of being hot and/or cold deformed. A cast iron is used in its cast form. Steels and cast irons are the most widely used and least expensive metallic materials on earth. This Chapter introduces the metallographer to the various types of steels and cast irons and explains how they are classified and defined. The classification includes the plain carbon and alloy steels as well as the gray, white, ductile, and malleable cast irons, beginning with the steels.

Steels

There are thousands of different steel compositions currently available around the world. To the beginning metallographer, the variety and terminology may at first be overwhelming. In fact, the way that steels are classified may be quite confusing even to the seasoned metallographer and metallurgist. However, in many cases the steels fall into a limited number of well-defined classes. An attempt is made in this chapter to summarize these classes. More detailed information can be found in the *ASM Handbook* (Volume 1), the selected references listed at the end of the Chapter, and in the Appendix.

Classification of Steels

Generally, the carbon and low-alloy steels come under a classification system based on composition. The higher-alloy steels (the stainless, heat-resistant, wear-resistant steels, etc.) can be classified according to many different systems, including composition, microstructure, application, or specification. The flow diagram in Fig. 1.1 shows very generally how steels are classified. On the left side, they are classified by commercial name or application, and on the right side, by microstructure. The flow diagram may look complicated at first, but this Chapter attempts to explain it. Mostly, the classifications on the left side of the diagram are examined.

The easiest way to classify steels is by their chemical composition. Various alloying elements are added to iron for the purpose of attaining certain specific properties and characteristics. These elements include, but are not limited to, carbon, manganese, silicon, nickel, chromium, molybdenum, vanadium, columbium (niobium), copper, aluminum, titanium, tungsten, and cobalt. The functions of each of these elements and others are listed in Table 1.1. Most steels contain several of these elements, particularly, carbon, manganese, and silicon.

Formal Classification Systems

Many nations have their own classification system for steels and cast irons. Because of the complexity of these different classification systems, only those used in the United States are described in this Chapter.

The American Iron and Steel Institute (AISI) and Society of Automotive Engineers (SAE) System. For many decades, plain carbon, low-alloy steels have been classified by composition using a system devised by SAE and eventually AISI. In this chapter, the steels thus classified have "AISI/SAE" before the steel code number, for example, AISI/SAE 1040 steel. The system is based solely on composition. In the four- or five-digit code designation, the last two or three digits represent the carbon content (three digits for steels with a carbon content of 1.00% and above), and the first two digits represent the compositional class. Thus, in the example of AISI/SAE 1040 mentioned previously, the "10" represents the class of plain carbon steels, and the "40" represents the carbon content of 0.40% C. The AISI/SAE designations and compositions are listed in the Appendix.

The American Society for Testing and Materials (ASTM) System. Another system was devised by ASTM. This system is not based on composition but on the steel product and application, for example, railroad rails, boiler tubes, plate, and bolts. ASTM has devised a system of specifications that contain composition, mechanical properties, and other required characteristics of steels and cast irons. The ASTM system reaches far beyond ferrous materials and includes other materials, such as rubber, cement, wood, fabric, copper, and so on. The American Society of Mechanical Engineers (ASME) devised a similar system, but it is generally limited to boiler and heat exchanger steels and other materials that are covered by the boiler code specifications.

The Unified Numbering System (UNS). Because of the confusion of different systems, a number of technical societies and U.S. governmental agencies devised what is known as the Unified Numbering System. There is a UNS designation for each steel composition, and it consists of a letter followed by five digits. The system fully incorporates the AISI/SAE system. For example, the UNS designation for AISI/SAE 1040 is G10400. The letter "G" represents the AISI/SAE plain carbon and alloy steels. Other ferrous alloys have different letters, such as "F" for cast irons and cast steels (cast steels can also have the letter "J"), "D" for steels with specific mechanical properties, "S" for heat- and corrosion-resistant steels, "T" for tool steels, and "H" for steels with enhanced hardenability. In this book, the AISI/SAE designations are favored only because they are, at the present time, more widely used than the UNS designations. However, in the reference tables in the Appendix, both designations are listed.

In this Chapter, all systems are used where appropriate. For some steels, it may be easier to use the AISI/SAE system, for others, the ASTM system. We first examine the way the steels are classified simply by composition, using the AISI/SAE system. This system has been established for many years and is widely used in industry.

Carbon and Low-Alloy Steels

The general category of carbon and low-alloy steels encompasses plain carbon steels, alloy steels, high-strength low-alloy

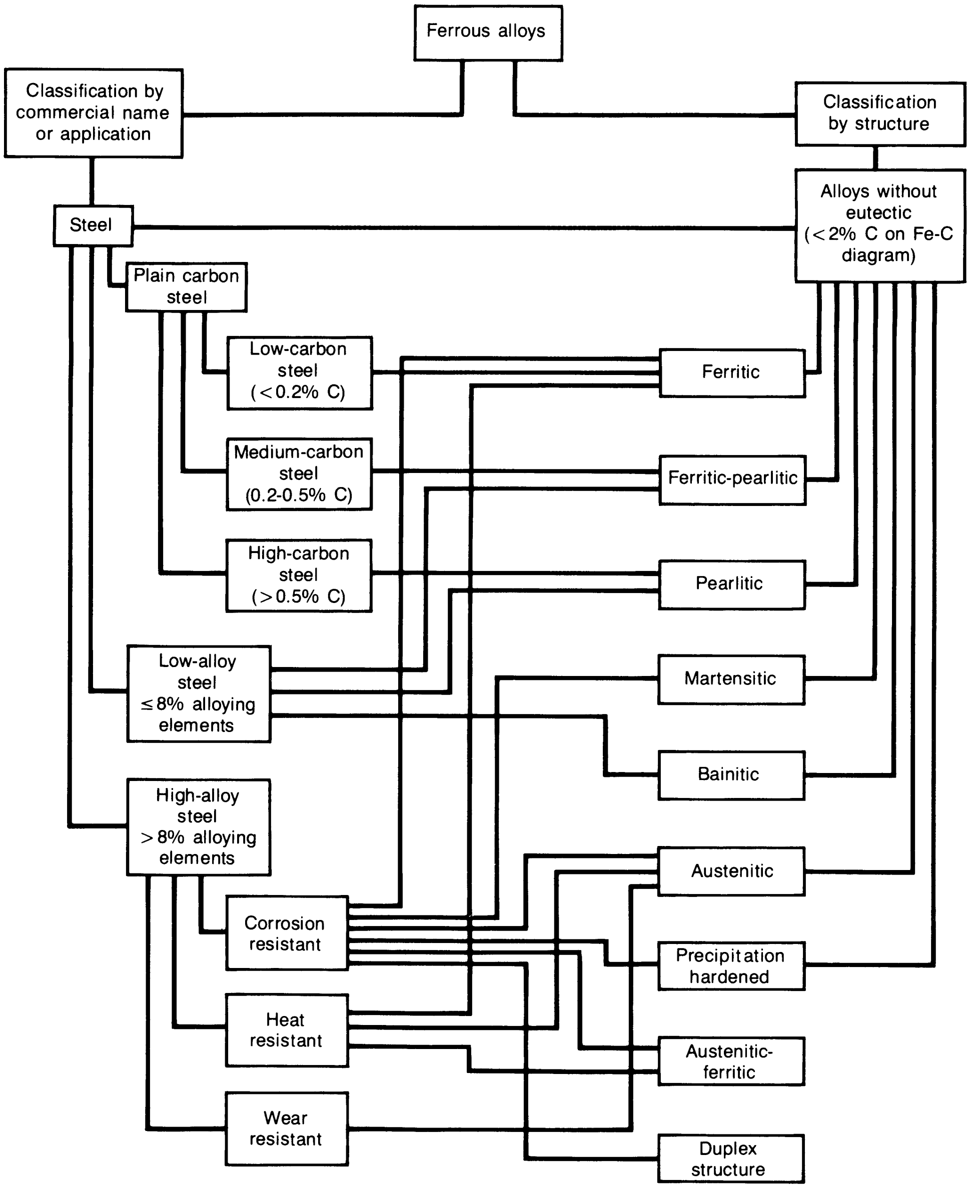

Fig. 1.1 Classification chart for steels

Table 1.1 Essential and incidental elements in steel and cast iron

Element	Function
Carbon (C)	An essential alloying element in most steels. Added to increase solid-solution strength and hardness as well as to increase hardenability. Dissolves in iron to form ferrite and austenite. Combines with iron to form a carbide (cementite-Fe_3C). The carbide is a component of pearlite.
Manganese (Mn)	An essential alloying element in most steels. Added to increase solid-solution strength and hardness as well as to increase hardenability. A weak carbide former (greater than iron). Counteracts brittleness caused by sulfur (iron sulfide) through the formation of a manganese sulfide (MnS). High levels of manganese produce an austenitic steel with improved wear and abrasion resistance.
Phosphorus (P)	Usually considered an impurity in most steels. Can be added to low-carbon steels to increase strength and hardness. Improves machinability of free-machining steels. Promotes temper embrittlement. Forms an undesirable iron phosphide (Fe_3P) at high phosphorus levels (especially in cast irons)
Sulfur (S)	Usually considered an impurity in steel. Added to special steels for improved machinability
Silicon (Si)	An essential alloying element in most steels. Added to increase solid-solution strength and hardness as well as to increase hardenability. Is added to molten steel to remove oxygen (deoxidize). As a result of deoxidation, can form silicate stringers (silicon dioxide inclusions). Does not form a carbide in steels. Improves oxidation resistance. Added to special steels to improve electrical and magnetic properties as well as hardenability. Increases susceptibility to decarburization. Promotes graphitization in cast irons
Nickel (Ni)	An essential alloying element in some steels. Added to increase solid-solution strength and hardness as well as to increase hardenability. Toughens steels, especially at low temperatures. Does not form a carbide in steel. Renders high-chromium stainless steels austenitic
Chromium (Cr)	An essential alloying element in some low-alloy steels and all stainless steels. Added to slightly increase solid-solution strength and hardness as well as to increase hardenability. Increases resistance to corrosion and high-temperature oxidation. A carbide former (greater than manganese); its carbides improve wear and abrasion resistance and provide high-temperature strength.
Molybdenum (Mo)	An essential alloying element in some low-alloy steels and tool steels. Added to increase solid-solution strength and hardness as well as to increase hardenability. A strong carbide former (stronger than chromium). Improves high-temperature properties, including creep strength. Counteracts temper embrittlement. Enhances corrosion resistance in stainless steels
Copper (Cu)	Usually considered an impurity or tramp element in most steels, because it promotes hot shortness. Added to some steels for improved corrosion resistance. Added in special steels for increased strength and hardness through heat treating (aging). Very insoluble in iron at room temperature and does not form a carbide
Cobalt (Co)	An essential alloying element in some steels. Added to increase strength and hardness. Improves hot hardness. Weak carbide former. An important element in some tool steels and heat-resistant steels. Decreases hardenability
Tungsten (W)	An essential alloying element in some steels. Added to increase solid-solution strength and hardness as well as to increase hardenability. Strong carbide former; the carbides form hard, abrasion-resistant particles in tool steels.
Vanadium (V)	An important element in microalloyed steels. Added to increase strength and hardness of steel by grain-size control (grain refinement) as well as to increase hardenability. Strong nitride former; also forms a carbide. Minimizes loss in strength during tempering
Columbium (Cb) Niobium (Nb)	An important element in microalloyed steels. Added to increase strength and hardness of steel by grain-size control (grain refinement) as well as to increase hardenability. Strong carbide former; also forms a nitride
Aluminum (Al)	An important alloying element in nitrided steels and deep-drawing sheet steels. Added to increase strength and hardness of steel by grain-size control (grain refinement). A common deoxidizer. Forms undesirable alumina inclusions (aluminum oxides). A strong nitride former. Does not form a carbide in steel
Titanium (Ti)	An important element in microalloyed steels. Added to increase strength and hardness of steel by grain-size control (grain refinement). Very strong carbide and nitride former. Important element to "getter" or tie up nitrogen in steels (protects boron from nitrogen in boron-treated steels). Also a strong deoxidizer. Can combine with sulfur to form titanium sulfides
Boron (B)	Added to steel to increase hardenability. Enhances the hardenability characteristics of other alloying elements. Added to steel for nuclear reactor applications because of its high cross section for neutrons
Nitrogen (N)	Added to some microalloyed steels to increase the amount of nitrides required for strengthening or grain-size control (e.g., in a vanadium steel)
Lead (Pb)	Insoluble in steel. Added to special leaded steels for improved machinability. Environmentally sensitive
Bismuth (Bi)	Similar to lead. Added to special steels for improved machinability
Tin (Sn)	An impurity or tramp element in steel. Promotes temper embrittlement
Antimony (Sb)	An impurity or tramp element in steel. Promotes temper embrittlement
Arsenic (As)	An impurity or tramp element in steel. Promotes temper embrittlement
Oxygen (O)	Undesirable in steel. Combines with other elements (manganese, silicon, aluminum, titanium, etc.) to form oxide inclusions that can degrade toughness and fatigue resistance. Usually minimized in steel by deoxidation with aluminum and/or silicon and vacuum degassing
Hydrogen (H)	Undesirable in steel. If entrapped, can cause crack formation (hydrogen flakes, microcracks, etc.). Usually minimized in liquid steel by vacuum degassing or slow cooling after the austenite-to-ferrite transformation
Calcium (Ca)	Added to steel for sulfide shape control (combines with sulfur to form rounded, undeformable inclusions). Strong deoxidizer. Forms calcium oxide and calcium aluminate inclusions
Zirconium (Zr)	Added to steel for sulfide shape control (forms rounded, undeformable zirconium sulfides). Strong deoxidizer. Forms zirconium oxide and is a strong nitride former
Cerium (Ce)	Added to steel for sulfide shape control (forms rounded, undeformable cerium sulfide inclusions). Strong deoxidizer
Magnesium (Mg)	Added to liquid cast iron to nucleate graphite nodules in ductile (nodular) iron

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(HSLA) steels, and a variety of other low-alloy steels. Each of these subcategories is described in the following sections.

Plain Carbon Steels

The more commonly used steels are classified according to composition. These steels include the plain carbon steels, with the following general subclasses:

Subclass	Carbon content (a), %
Low-carbon steels	Under 0.2
Medium-carbon steels	0.2–0.5
High-carbon steels	Above 0.5

(a) All percentages in this Chapter are weight percent, unless otherwise noted.

AISI/SAE Classification System for Plain Carbon Steels. The plain carbon steels can be further classified by specific composition according to the AISI and SAE designations. As a specific example, the designation AISI/SAE 1040 signifies a medium-carbon steel with a nominal carbon content of 0.40% and with the following range of composition:

Element	Content, %
Carbon	0.37–0.44
Manganese	0.60–0.90
Phosphorus	0.040 max
Sulfur	0.050 max

The AISI/SAE designations for the plain carbon steels are listed in the Appendix.

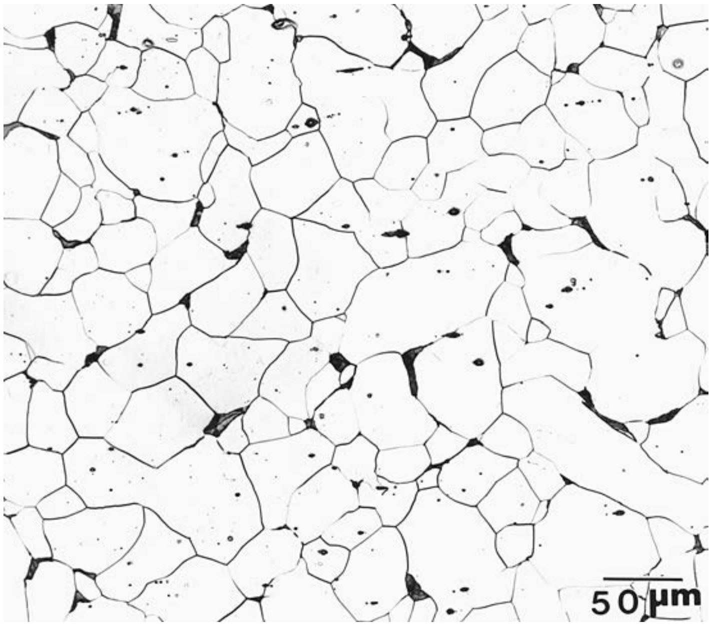

Fig. 1.2(a) Micrograph of low-carbon AISI/SAE 1010 steel showing a matrix of ferrite grains (white etching constituent) and pearlite (dark etching constituent). Etched in Marshall's reagent followed by 2% nital. 200×

The microstructures of typical low-carbon, medium-carbon, and high-carbon steels are shown in Fig.1.2(a), (b), and (c), respectively. The low-carbon steel is represented by an AISI/SAE 1010 steel, the medium-carbon steel by an AISI/SAE 1040 steel, and the high-carbon steel by an AISI/SAE 1095 steel. As carbon content increases, the amount of pearlite (the dark etching constituent) increases. Actually, the amount of pearlite increases up to a maximum of 100% at a carbon content near 0.8%. Below

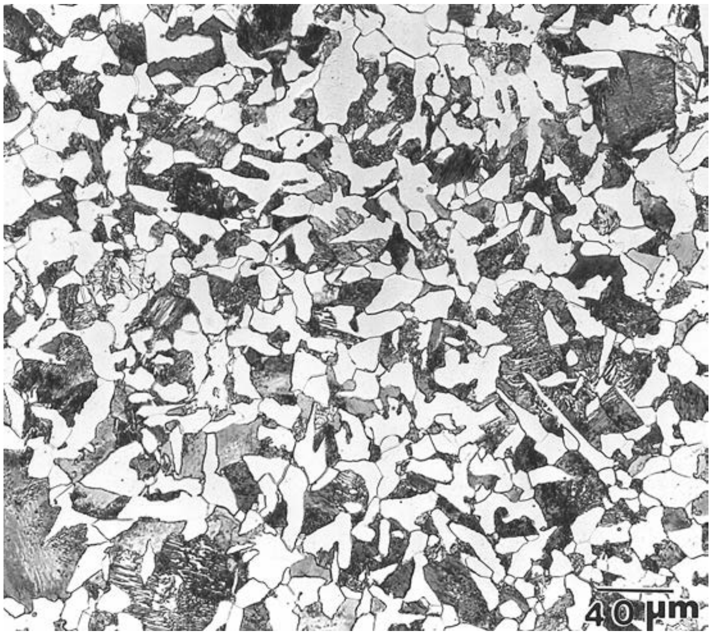

Fig. 1.2(b) Micrograph of medium-carbon AISI/SAE 1040 steel showing ferrite grains (white etching constituent) and pearlite (dark etching constituent). Etched in 4% picral followed by 2% nital. 300×

Fig. 1.2(c) Micrograph of high-carbon AISI/SAE 1095 steel showing a matrix of pearlite and some grain-boundary cementite. Etched in 4% picral. 500×

0.8% C, the other constituent in the microstructure is ferrite, as seen in Fig. 1.2(a) and (b). Above 0.8%, the other constituent is cementite, as seen in Fig. 1.2(c). More details about these constituents are found in the next Chapter.

Within the AISI/SAE plain carbon steel designations there are five subclasses, namely 10*xx*, 11*xx*, 12*xx*, 13*xx*, and 15*xx*. These are broadly based on the following categories of steel composition:

AISI/SAE designation	Type of steel
10*xx*	Plain carbon: Mn 1.00% max
15*xx*	Plain carbon: Mn 1.00–1.60%
13*xx* (a)	Plain carbon: Mn 1.60–1.90%
11*xx*	Plain carbon: resulfurized
12*xx*	Plain carbon: resulfurized and rephosphorized

(a) Actually, the 13*xx* series of steels is classified as low-alloy steels because of the high manganese level. (Generally a steel with an alloying element content above 1.5% is considered a low-alloy steel; above 8% it is considered a high-alloy steel.) However, in the case of the 13*xx* series, one is basically dealing with a simple extension of the 10*xx* and 15*xx* plain carbon steels.

The AISI/SAE 15*xx* and 13*xx* series represent high-manganese, plain carbon steels. The higher manganese levels impart higher hardness and strength to the steels. The complete series of AISI/SAE 15*xx* and 13*xx* steels are listed in the Appendix.

The 11*xx* series of plain carbon, resulfurized steels contains intentionally added sulfur. The sulfur does not actually alloy with the iron but combines with manganese to form manganese sulfide (MnS) inclusions. The sulfur level is much higher in the 11*xx* series than the 10*xx* series of plain carbon steels where sulfur is generally considered as an impurity. The higher sulfur level in the resulfurized steels imparts improved machinability to the steel because of the chip-breaking effect of the manganese sulfides. An example of a resulfurized steel is AISI/SAE 1140 steel, with the following composition:

Element	Content, %
Carbon	0.37–0.44
Manganese	0.70–1.00
Phosphorus	0.040 max
Sulfur	0.08–0.13

For a given carbon content, the manganese levels are slightly higher in the 11*xx* series than in the previously discussed 10*xx* series. The higher manganese levels compensate for the higher sulfur levels, because manganese is added to tie up all the sulfur to form manganese sulfides. The AISI/SAE 11*xx* series of resulfurized steels is listed in the Appendix.

The AISI/SAE 12*xx* series represents resulfurized and rephosphorized, plain carbon steels that are also free-machining steels, with both sulfur and phosphorus as alloy additions. The phosphorus addition increases the strength of the steel and promotes chip breaking during machining operations. In order to limit the strength of the steel, the carbon content is restricted to a level under 0.15%. For example, an AISI/SAE 1213 steel is represented by the following composition:

Element	Content, %
Carbon	0.13 max
Manganese	0.70–1.00
Phosphorus	0.07–0.12
Sulfur	0.24–0.33

Fig. 1.3 shows the microstructure of a typical resulfurized, rephosphorized steel containing manganese sulfides (the oblong, gray particles). The AISI/SAE 12*xx* series of steels is listed in the Appendix.

As has been shown, the AISI/SAE system for classifying the plain carbon steels is quite simple and is based solely on chemical composition. However, many plain carbon and alloy steels are classified according to a much more complex system based on the product application, the chemical composition, and the mechanical properties. This system has been devised by ASTM. The ASTM system consists of a set of detailed specifications for each steel, depending upon how it is used. Thus, there are specifications for plate, strip, sheet, rod, railroad rails, pipe, bolts, wire, nuts, structural shapes, and so on. The system is much different than the AISI/SAE system, and it is only touched on in this Chapter.

The ASTM Specification System for Plain Carbon Steels. ASTM has very elaborate specifications for steels that include the type of product (sheet, plate, bar, wire, rail, etc.), the composition limits, and the mechanical properties. The ASTM specifications for iron and steel products comprise six 25 mm (1 in.) thick books weighing over 5.5 kg (12 lb). (The specifications can also be obtained in compact diskette form.) The specification code consists of the letter "A" followed by a number. A partial list of the plain carbon steels according to the ASTM specification system is given subsequently:

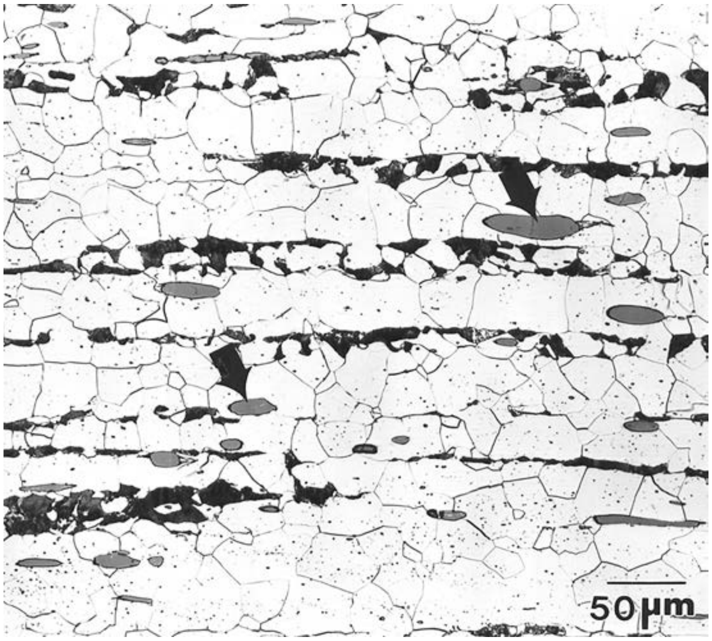

Fig. 1.3 Micrograph of a resulfurized, rephosphorized AISI/SAE 1213 steel showing manganese sulfide inclusions (the gray, oblong particles marked by arrows). The remaining microstructure is ferrite (white etching constituent) and pearlite (dark etching constituent). Etched in 4% picral followed by 2% nital. 200×

ASTM designation	Type of steel
A 1	Carbon steel, tee rails
A 36	Structural steel
A 131	Structural steel for ships
A 228	Steel wire, music spring quality
A 307	Carbon steel, bolts and studs, 420 MPa (60 ksi) tensile strength
A 510	Carbon steel wire rods
A 529	Structural steel with 290 MPa (42 ksi) minimum yield point
A 570	Steel, sheet and strip, carbon, hot rolled, structural quality
A 709	Structural steel for bridges

As examples, two of these ASTM specifications are described in more detail: ASTM A 1 for railway rails and ASTM A 36 for structural steels (structural beams, plate, etc.).

ASTM A 1 requires that railroad rails have certain composition limits and a minimum hardness. For example, for a common rail size of 60 kg/m (132 lb/yd) the requirements are:

Carbon	0.72–0.82%
Manganese	0.80–1.10%
Phosphorus	0.035% max
Sulfur	0.040% max
Silicon	0.10–0.20%
Hardness	269 HB min

The microstructure of a typical ASTM A 1 rail steel is shown in Fig. 1.4. The microstructure is 100% pearlite.

ASTM A 36 for structural steels is very different from ASTM A 1 for rail steel in that it specifies only a minimum carbon content and certain tensile properties. ASTM A 36 has the following requirements:

Carbon	0.26% max
Yield point	248 MPa (36 ksi) min
Tensile strength	400–552 MPa (58–80 ksi)
Total elongation (in 50 mm, or 2 in.)	21% min

The microstructure of a typical ASTM A 36 structural steel is shown in Fig. 1.5. The microstructure is a mixture of pearlite and ferrite, with some manganese sulfide stringers.

The ASTM specifications illustrated previously are rather simple. As the product becomes more critical and the composition more complex, the requirements expand considerably.

Alloy Steels

The alloy steels are generally divided into two classes: the low-alloy steels and the high-alloy steels. They are divided according to composition as follows:

Type	Alloying elements, %
Low-alloy steels	<8
High-alloy steels	>8

The AISI/SAE Classification System for Low-Alloy Steels. As with the plain carbon steels, there is an established classification system of AISI/SAE designations for the low-alloy steels. The classification is based on the principal alloying element(s) in the steel. These principal elements include carbon, manganese, silicon, nickel, chromium, molybdenum, and vanadium. Each element, either singly or in combination with other elements, imparts certain properties and characteristics to the steel. The role of each element was described in Table 1.1. The subsequent list gives the breakdown of the AISI/SAE classification for the low-alloy steels:

Fig. 1.4 Micrograph of ASTM A 1 rail steel showing the fully pearlitic microstructure. Etched in 4% picral. 500×

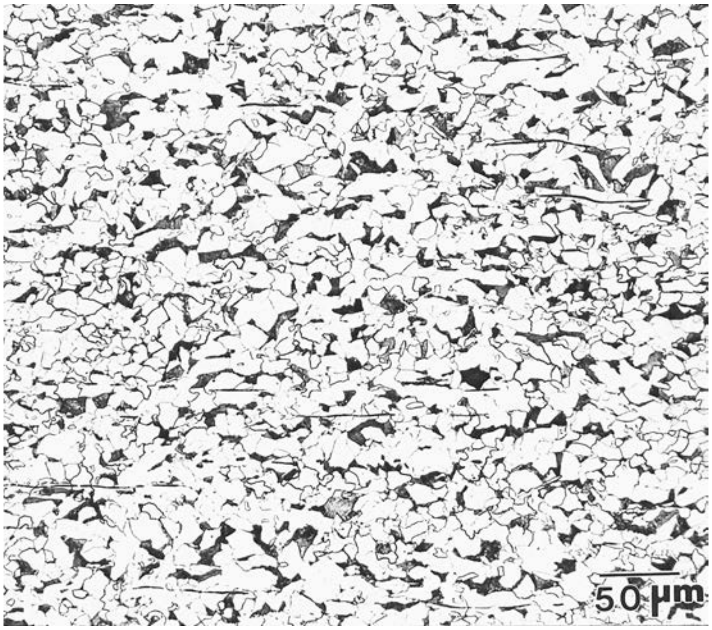

Fig. 1.5 Micrograph of ASTM A 36 structural steel showing a microstructure consisting of ferrite (light etching constituent) and pearlite (dark etching constituent). Etched in 4% picral followed by 2% nital. 200×

AISI/SAE designation	Type of steel
13*xx*	1.75% Mn steels
40*xx*	0.25% Mo steels
41*xx*	0.50 and 0.95% Cr-0.12 and 0.25% Mo steels
43*xx*	1.80% Ni-0.50 and 0.80% Cr-0.25 and 0.40% Mo steels
44*xx*	0.40% Mo steels
46*xx*	0.85 and 1.80% Ni-0.20 and 0.25% Mo steels
47*xx*	1.05% Ni-0.45% Cr-0.20 and 0.35% Mo steels
48*xx*	3.5% Ni-0.25% Mo steels
50*xx*	0.28 and 0.50% Cr steels
51*xx*	0.80, 0.88, 0.95 and 1.00% Cr steels
50*xxx*	1.05–1.45% Cr steels
51*xxx*	1.03% Cr steels
61*xx*	0.60 and 0.95% Cr-0.13 and 0.15% (min) V steels
81*xx*	0.30% Ni-0.40% Cr-0.12% Mo steels
86*xx*	0.55% Ni-0.50% Cr-0.20% Mo steels
87*xx*	0.55% Ni-0.50% Cr-0.25% Mo steels
88*xx*	0.55% Ni-0.50% Cr-0.35% Mo steels
92*xx*	1.40 and 2.00% Si-0.00 and 0.7% Cr steels
93*xx*	3.25% Ni-1.20% Cr-0.12% Mo steels
94*xx*	0.50% Ni-0.40% Cr-0.98% Mo steels
*xx*B*xx*	Boron steels ("B" denotes boron)
*xx*L*xx*	Leaded steels ("L" denotes lead)

The composition ranges for the previously mentioned AISI/SAE low-alloy steels (except for the boron and leaded steels) are listed in the Appendix. There are many low-alloy steels that are not classified under the previously mentioned AISI/SAE system (some of these steels are also listed in the Appendix). Thus, the situation with low-alloy steels becomes much more complicated. For example, HY-80, a steel widely used for high-strength plate and forging applications, is a Ni-Cr-Mo steel but does not have an AISI/SAE designation. This particular steel is covered by a specification designation, ASTM A 543. ASTM has dozens of specifications for low-alloy steels. This system is discussed subsequently.

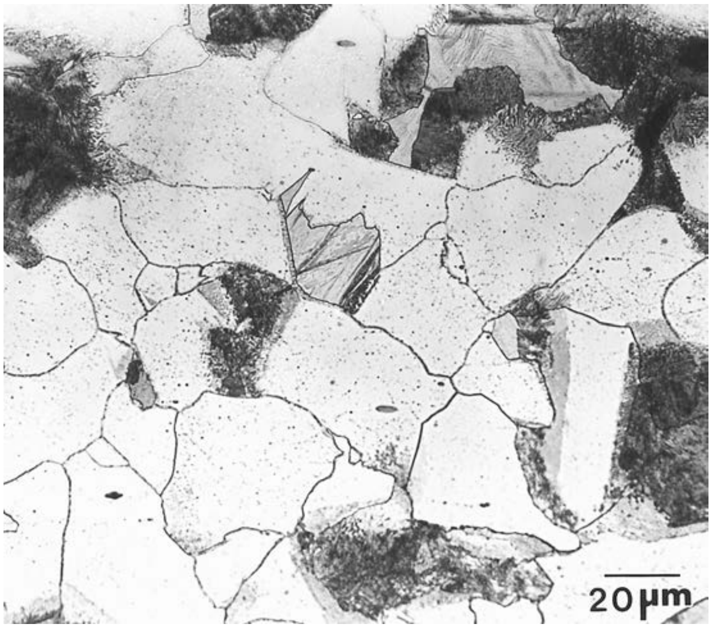

Fig. 1.6 Micrograph of ASME SA213-T22 boiler tube steel showing a microstructure consisting of ferrite (light etching constituent) and a small amount of pearlite (dark etching constituent). Light tan areas are martensite. Etched in 4% picral. 200×

The ASTM Specification System for Low-Alloy Steels. As with the plain carbon steels, ASTM specifications also cover many of the low-alloy steels. However, as mentioned previously, the ASTM system is driven by the application for the particular steel. The system for low-alloy steels is quite large and is only touched on in this chapter; for example, a fairly common low-alloy steel is 2¼Cr-1Mo steel. In the ASTM system there are 13 separate specifications covering this steel, depending on the product form that is manufactured, as shown subsequently:

Product form	ASTM designations
Forgings	A 182, A 336, and A 541
Tubes	A 199, A 220, and A 213
Pipe	A 335, A 369, and A 462
Castings	A 217 and A 356
Plate	A 387 and A 542

As an example, ASTM A 213 has the title "Seamless Ferritic and Austenitic Alloy Steel for Boiler, Superheater, and Heat Exchanger Tubes." The standard actually covers 14 different grades of ferritic steels and 14 different grades of austenitic steels. The 2¼Cr-1Mo steel is grade T22. Because the grade is used in tubing for boilers and heat exchangers, it is also part of the specification system of ASME. The ASME adopts the ASTM code and places an "S" before it as, for example, ASME SA213 type T22. The ASTM and ASME grade (type) T22 has the following composition:

Element	Content, %
Carbon	0.15 max
Manganese	0.30–0.60
Silicon	0.50 max
Chromium	1.90–2.60
Molybdenum	0.87–1.13

The microstructure of a typical ASTM A 213 grade T22 steel (ASME SA213 type T22) is shown in Fig. 1.6. It is interesting to note that if the same steel was used for a forging or plate, it may have a different microstructure because of the different specified heat treatment. Even for tubes (ASTM A 213), it can be furnished in the full-annealed, isothermal annealed, or normalized and tempered condition. Each condition would have a different microstructure.

High-Strength, Low-Alloy Steels

Although many of the previously mentioned AISI/SAE low-alloy steels also have high strength and, in some cases, ultrahigh strength (a yield strength above 1380 MPa, or 200 ksi), there is a rather loose class of steels called HSLA steels that do not fit the previously mentioned AISI/SAE classification. Although attempts have been made by AISI, SAE, and ASTM to classify the HSLA steels, the metallographer can easily become confused about these classifications. An attempt is made here to explain the basic classification systems.

These HSLA steels are a group of low- and medium-carbon steels that generally use small amounts of alloying elements to attain yield strengths usually above about 345 MPa (50 ksi) in the hot-rolled, cold-rolled, annealed, stress-relieved, acceleratedcooled, direct-quenched, or normalized condition. In some cases they are called microalloyed steels because of the small amounts of vanadium, columbium (niobium), and/or titanium that are added for grain refinement and precipitation strengthening. The microstructure of a typical microalloyed steel is shown in Fig. 1.7.

The ASTM Specification System. ASTM specifies most of the HSLA steels according to composition, mechanical property requirements, and application. A partial list of ASTM specifications for various HSLA steels is given subsequently (a complete list can be found in the Appendix):

ASTM designation	Type of steel
A 242	HSLA structural steel
A 572	HSLA columbium (niobium)-vanadium structural steel
A 588	HSLA structural steel with 345 MPa (50 ksi) minimum yield point
A 656	HSLA hot-rolled structural V-Al-N and titanium-aluminum steels
A 714	HSLA welded and seamless steel pipe
A 715	HSLA, hot-rolled sheet and strip, and sheet steel, cold-rolled, high-strength, low-alloy, with improved formability
A 808	HSLA with improved notch toughness
A 871	HSLA steel with atmospheric corrosion resistance

Within each ASTM specification, one can find the mechanical property requirements as well as the range of chemical composition allowed. There are numerous other ASTM specifications involving low-alloy steels, depending on the particular application.

The SAE Classification System for High-Strength, Low-Alloy Steels. The Society of Automotive Engineers has developed a classification for HSLA steels used in automotive applications. The steels are classified according to minimum yield strength level. The latest SAE classification system for HSLA steels consists of a three-digit code representing the minimum yield strength in ksi. Thus, a code of 080 would represent a 552 MPa (80 ksi) minimum yield strength. In the SAE system, there are usually one or more letters following the three-digit number to describe the chemical composition, carbon level, or deoxidation practice. The composition could be structural quality (S), low-alloy (L), or weathering (W). The carbon content could be low (L) or high (H). The deoxidation practice could be killed (K), killed plus inclusion control (F), or nonkilled (O). For example, SAE grade 080XLK would represent a low-alloy (X), low-carbon (L), killed, inclusion-controlled (K) steel with a minimum yield strength of 552 MPa (80 ksi). (The older SAE J410.c system would have a grade code of 980XK.)

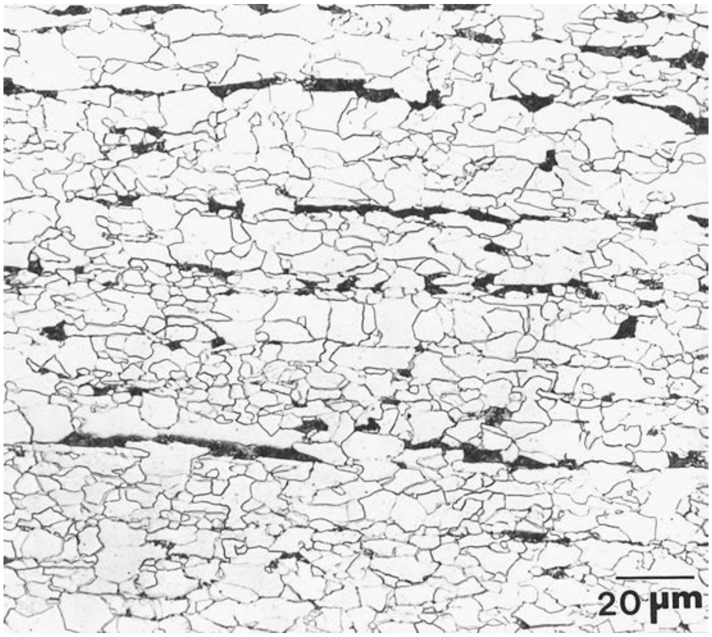

Fig. 1.7 Micrograph of a microalloyed 450 MPa (65 ksi) yield strength linepipe steel showing a microstructure consisting of ferrite (light etching constituent), a small amount of pearlite (dark etching constituent), and martensite (gray etching constituent). Etched in 4% picral followed by 2% nital. 500×

SAE designation	Content, %		
	Carbon	Manganese	Other
050XLK	0.23 max	1.35 max	Cb, V
060XLK	0.26 max	1.45 max	Cb, V, N
070XLK	0.26 max	1.65 max	Cb, V, N
080XLK	0.26 max	1.65 max	Cb, V, N

The AISI Classification System for High-Strength, Low-Alloy Steels. The AISI classification for high-strength, low-alloy steels is somewhat similiar to the SAE classification system, except that it does not have a carbon level but includes more strength levels and the dual-phase steels. The dual-phase steels, which contain about 10 to 20 vol% martensite in a matrix of ferrite, have a "D" as part of the designation. Also, dual-phase steels are different from other HSLA steels in that they are not generally classified by minimum yield strength but by minimum tensile strength in ksi. For example, an AISI code of DF090T would be a dual-phase (D) killed steel with inclusion shape control (F) and has a minimum tensile strength (T) of 620 MPa (90 ksi). A typical microstructure of a dual-phase steel is shown in Fig. 1.8.

Some HSLA steels have commercial trade names. Recent designations HSLA 80 and HSLA 100 are being used for steels of a very specific steel composition with a minimum yield strength level of 552 MPa (80 ksi) and 690 MPa (100 ksi). In reality, there can be many HSLA 80 and HSLA 100 steels, depending upon composition, thermomechanical treatment, and heat treatment. Thus, there is not a standard classification system that encompasses all high-strength, low-alloy steels.

Other Low-Alloy Steels

There are many low-alloy steels that are not designed for just their room-temperature strength properties. These steels have additional properties that are important, such as corrosion or heat resistance and formability.

Low-Alloy Steels for High-Temperature Properties. An example of a low-alloy steel that is used for its high-temperature properties is ASTM A 470 turbine rotor steel. These steels are used in steam turbines for electric power generation and usually contain combinations of nickel, chromium, molybdenum, and/or vanadium. An example of the microstructure of ASTM A 470 rotor steel is shown in Fig. 1.9.

Low-Alloy Steels for Improved Corrosion Resistance. There are a number of low-alloy steels that have improved corrosion resistance. These steels usually have additions of copper, nickel, or chromium and are called weathering steels. The ASTM specifications cover several of these steels.

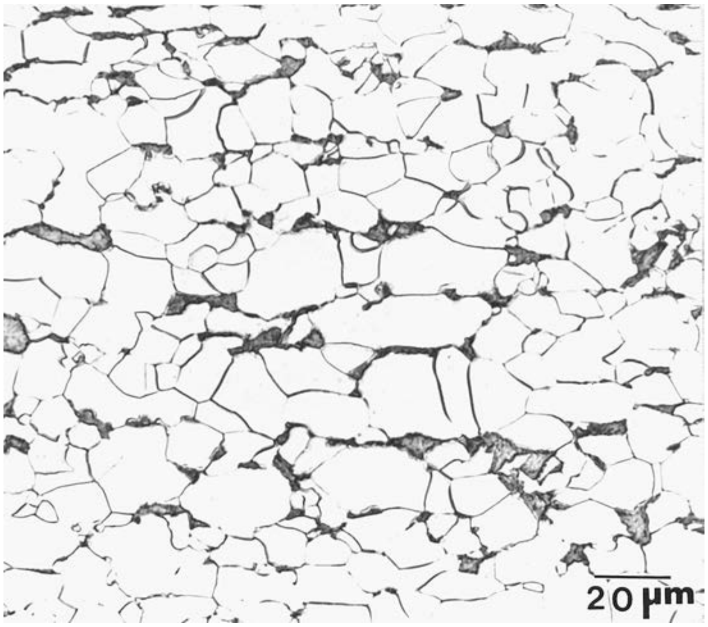

Fig. 1.8 Micrograph of AISI DF090T dual-phase steel showing a microstructure consisting of ferrite (light etching constituent) and a small amount of martensite (dark etching constituent). Etched in 4% picral. 500×

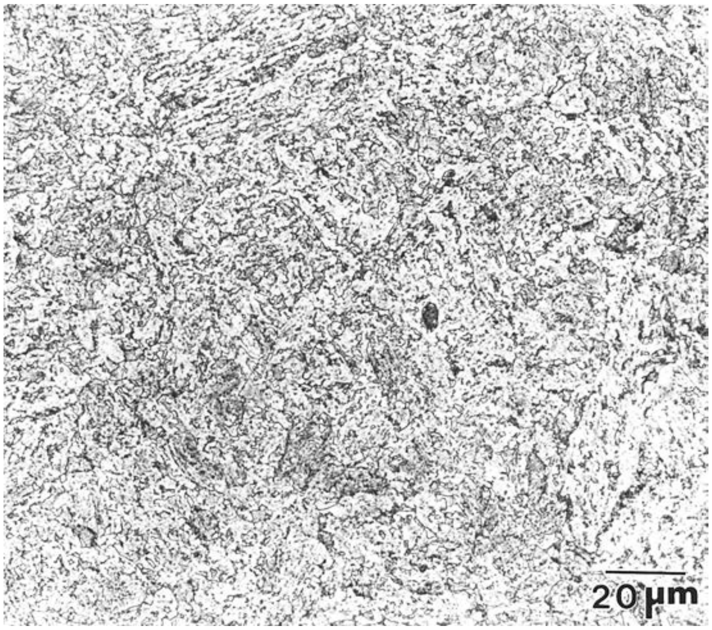

Fig. 1.9 Micrograph of ASTM A 470 rotor steel showing a microstructure consisting of tempered upper bainite. Etched in 4% picral. 500×

Low-Alloy Steels with Formability. There are some steels that are designed for optimal formability in sheet-forming applications. One common steel is specified as drawing quality, special killed. This cold-rolled, low-carbon sheet steel has a specified aluminum content. The aluminum combines with nitrogen in the steel to form aluminum nitride precipitates during the annealing process. These aluminum nitride precipitates are instrumental in the development of a specific crystallographic texture in the sheet that favors deep drawing. Another type of steel used for applications requiring optimal formability is interstitial-free steel. In this very-low-carbon sheet steel, the interstitial elements, carbon and nitrogen, are combined with carbide- and nitride-forming elements, such as titanium and columbium (niobium). The steel is rendered "free" from these interstitial elements that degrade formability.

Bake-Hardenable, Low-Alloy Steels. Specific sheet steels have been designed to increase strength during the paint-baking cycle of automobile production. These bake-hardenable steels contain elements that develop compounds that precipitate at the paint-baking temperatures. These precipitates harden the steel.

Dual-Phase, Low-Alloy Steels. A special class of steels known as dual-phase steels are used in applications where the yield strength of the sheet is increased during the forming process itself. These steels are designed to have a microstructure consisting of about 10 to 20% martensite in a matrix of ferrite. The steels have relatively low yield strength before forming a particular component (e.g., a wheel rim) and develop strength by a process called continuous yielding. The dispersed martensite regions are required for this process. Dual-phase steels were discussed in an earlier section, and a typical microstructure is seen in Fig. 1.8.

As mentioned previously, many of the low-alloy steels are classified according to composition, properties, or application. The same is true for the high-alloy steels. Some of the high-alloy steels fall under a classification system described subsequently.

High-Alloy Steels

High-alloy steels generally contain more than 8% total alloying elements. These steels include the corrosion-resistant (stainless) steels, the heat-resistant steels, and the wear-resistant steels (tool steels). The stainless steels and the tool steels fall under an established classification system. First the corrosion-resistant steels are examined.

Corrosion-Resistant (Stainless) Steels

For the corrosion-resistant steels, the system established by the AISI is not based on composition, but on microstructure. Thus, the stainless steels are classified as austenitic, ferritic, austenitic-ferritic, martensitic, duplex, and precipitation-hardening types, as shown in the flow diagram in Fig. 1.1. Most of the steels are classified by a three-digit designation. The system is not as clearly organized as the AISI/SAE system for plain carbon steels, because the number designations overlap. For example, within the 4*xx* series, 405 and 409 designate ferritic stainless steels, while 403 and 410 designate martensitic stainless steels; within the 3*xx* series, 321 and 330 designate austenitic stainless steels, and 329 designates a duplex stainless steel. Therefore, the metallographer must be aware that the system for stainless steels is somewhat inconsistent. The basic classification system is discussed subsequently.

Austenitic Stainless Steels. These stainless steels have a microstructure of austenite at room temperature. Thus, they are nonmagnetic. Austenitic stainless steel (such as the popular type 304) has been called 18/8 stainless steel, because it contains nominally 18% Cr and 8% Ni. There are 30 compositional variations in the standard austenitic stainless steels, and a summary of the family relationships is shown in Fig. 1.10. All the

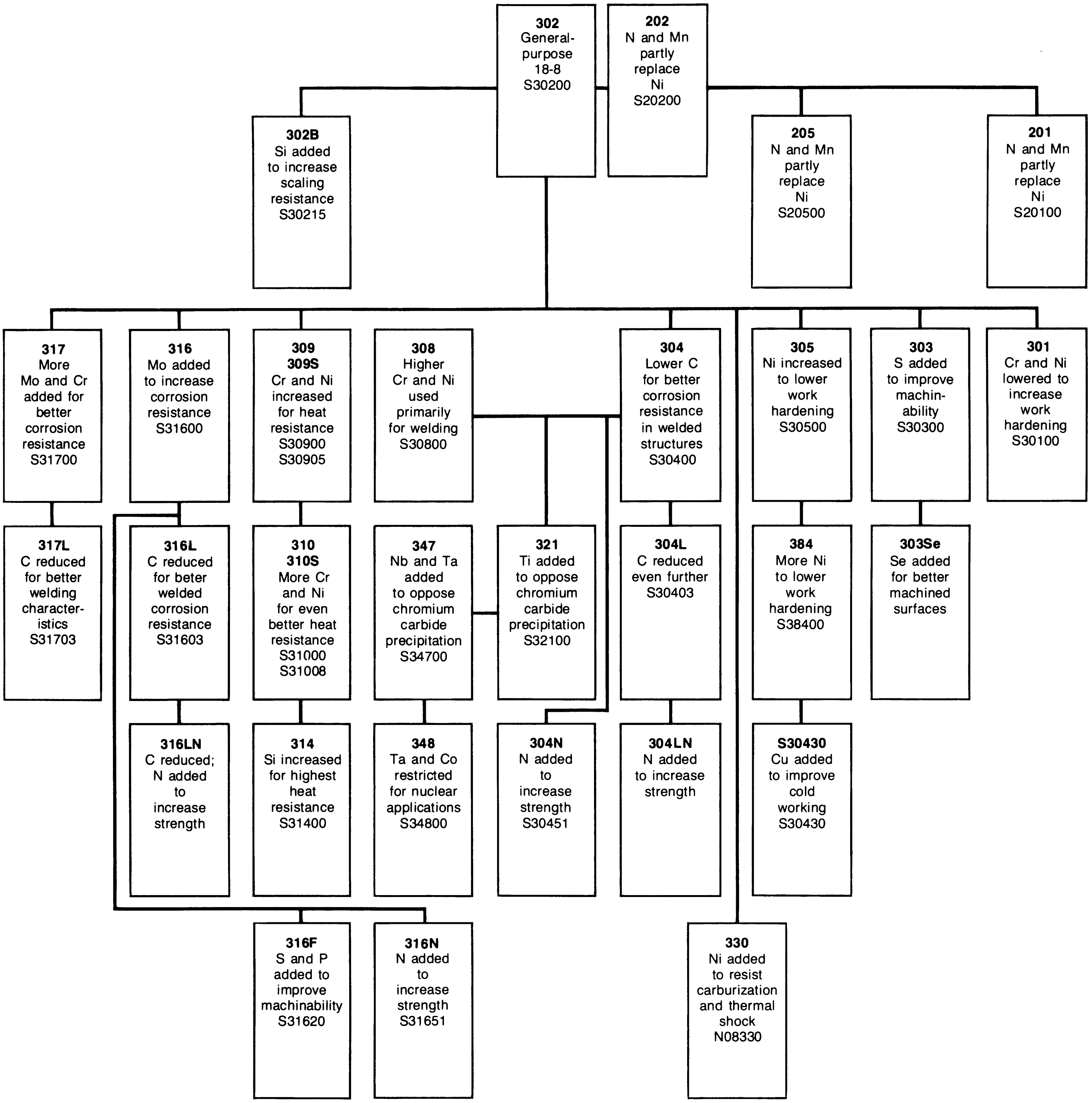

Fig. 1.10 Family relationships for standard austenitic stainless steels

austenitic stainless steels are essentially chromium-nickel alloys. The chromium varies between 15 and 24% and the nickel between 3 and 22%. The family is derived from two basic, general-purpose alloys, types 302 and 202. The type 302 grade expands into 26 other types with specific compositional variations to impart particular properties, for example, better weldability, increased strength, increased heat resistance, better corrosion resistance, and improved machinability. The type 202 series is limited to only three grades and was designed to replace nickel, a rather expensive alloying element, with nitrogen and manganese. The corrosion resistance of the austenitic stainless steels is superior to other types of stainless steel. The specific composition ranges for each of the austenitic stainless steels are listed in the Appendix. The microstructure of a typical austenitic stainless steel is shown in Fig. 1.11.

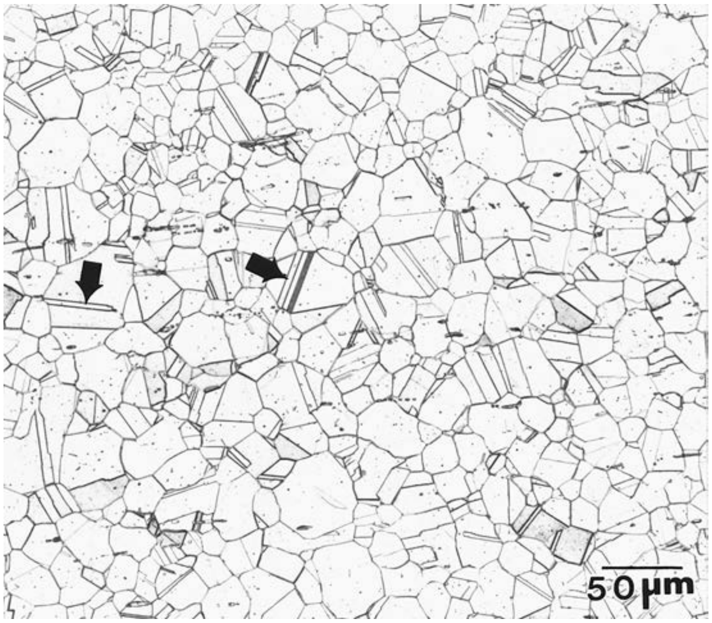

Fig. 1.11 Micrograph of AISI 316 austenitic stainless steel showing a microstructure consisting of 100% austenite. The straight-edged areas (marked by arrows) within the grains are annealing twins. Electrolytically etched in 60 parts nitric acid in 40 parts water, stainless steel cathode, at 6 V direct current. 200×

Ferritic Stainless Steels. The number of standard grades of ferritic stainless steel is much smaller than the austenitic grades. Fig. 1.12 shows the family relationships for the standard ferritic stainless steels. All the grades are variations on the basic, general-purpose type 430. The ferritic stainless steels are basically chromium steels with chromium ranging between 10.5 and 27%. These alloys deliberately lack high nickel contents, because nickel renders the steels austenitic (as previously mentioned). The ferritic stainless steels are the lower-cost stainless steels, because they contain less alloy, and they do not contain nickel (nickel is more expensive than chromium). The composition ranges of the ferritic stainless steels are listed in the Appendix. The microstructure of a free-machining ferritic stainless steel is shown in Fig. 1.13.

Martensitic Stainless Steels. The family relationships of the martensitic stainless steels are shown in Fig. 1.14. The compositional variations all lead from the general-purpose type 410. The

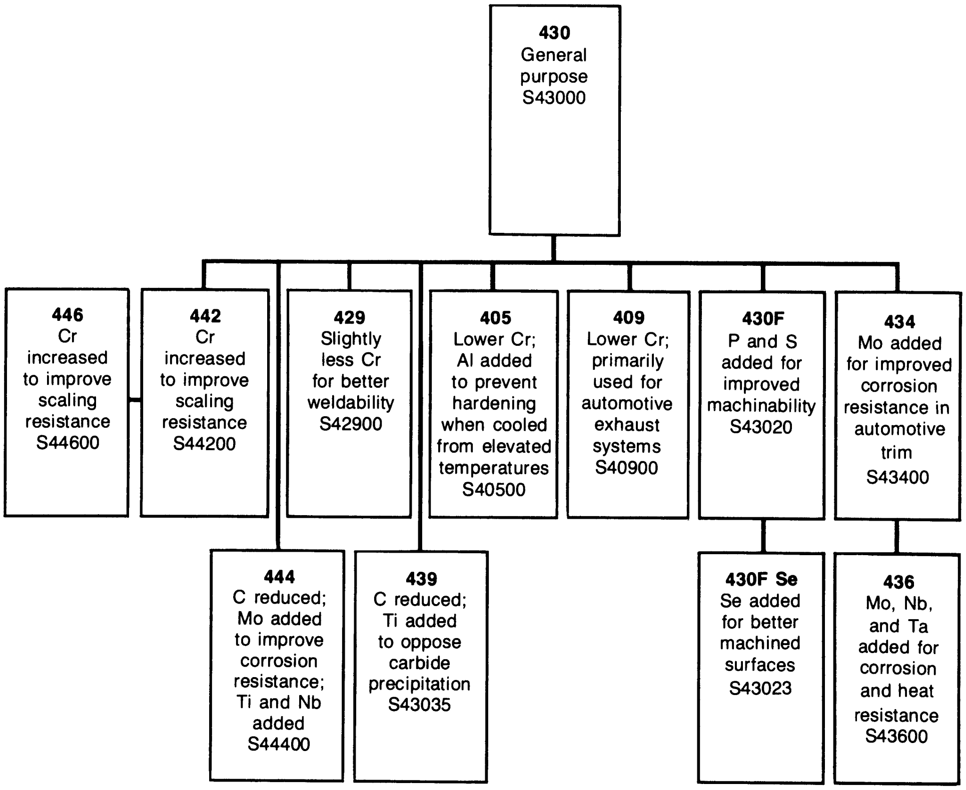

Fig. 1.12 Family relationships for standard ferritic stainless steels

specific compositional ranges are listed in the Appendix. The martensitic stainless steels are essentially chromium steels with higher carbon content than either the ferritic or austenitic stainless steels. The chromium and carbon contents are balanced to ensure a martensitic microstructure after hardening by heat treatment. These steels are harder than the austenitic or ferritic series of stainless steel and are used for applications such as knife blades. The microstructure of a typical martensitic stainless steel is shown in Fig. 1.15.

Duplex Stainless Steels. These steels have a mixed microstructure of ferrite and austenite. There is only one standard type of duplex stainless steel, grade 329, which contains 23 to 28% Cr, 2.5 to 5.0% Ni, and 1.0 to 2.0% Mo. The specific composition is listed in the Appendix. The duplex stainless steels have corrosion resistance similiar to an austenitic stainless steel but possess higher tensile and yield strengths and improved resistance to stress-corrosion cracking. The microstructure of a duplex stainless steel is shown in Fig. 1.16.

Precipitation-Hardening Stainless Steels. These steels are mainly chromium-nickel steels with precipitation-hardening elements such as copper, aluminum, and titanium. They can possess either a ferritic or martensitic microstructure. In the classification, the letters "PH", for precipitation hardening, may appear in the type code. The specific compositional variations are listed in the Appendix. The microstructure of a typical precipitation-hardening stainless steel is shown in Fig. 1.17.

Heat-Resistant Steels

These alloy steels are used for elevated-temperature applications. Unfortunately, there is not a basic classification system for these steels. This is because they include the low-alloy steels as well as the high-alloy stainless steels, tool steels, and iron-base superalloys. In other words, it depends on the elevated-temperature range and the application. At the lower temperatures, the low-alloy steels are adequate, whereas at higher temperatures, the higher-alloy steels are more appropriate. There are four AISI designated steels for elevated-temperature service. They are classified by a three-digit number beginning with "6". These steels are 601, 602, 603, and 610 and are all medium-carbon, low-alloy steels containing chromium, molybdenum, and vanadium. Many of the heat-resistant steels are considered pressure vessel steels and are covered under the ASME Boiler and Pressure Vessel Code. These steels usually contain chromium and molybdenum (sometimes vanadium). The popular 2 ¼ Cr-1 Mo steel comes under this family of steels (discussed earlier in this Chapter). Under ASME specifications, the grade codes begin with the letters "SA", and thus, a 2¼Cr-1Mo steel could have a code number SA-387 Gr22. The ASME grade code incorporates the ASTM grade code A 387 grade 22, which is the ASTM specification for 2¼Cr-1Mo steel for pressure vessels. Thus, in most cases the ASME grade codes are linked to the ASTM grade codes. A list of ASME compositions can be found in the Appendix. Many of the ferritic, austenitic, martensitic, and precipitation-hardened stainless steels are also used at elevated temperatures. In addition, many variants exist with proprietary names, such as Nitronic 60, Carpenter 18-18 Plus, Lapelloy, Greek Ascoloy, and so on. A list of compositions of the high-alloy, heat-resistant steels can be found in the Appendix. There are also several iron-base superalloys, including Discaloy, Haynes 556, Incoloy 800, and Pyromet CTX-1. A list of the compositions of the iron-base superalloys is also found in the Appendix. The microstructure of a typical iron-base superalloy (heat-resistant steel) is shown in Fig. 1.18.

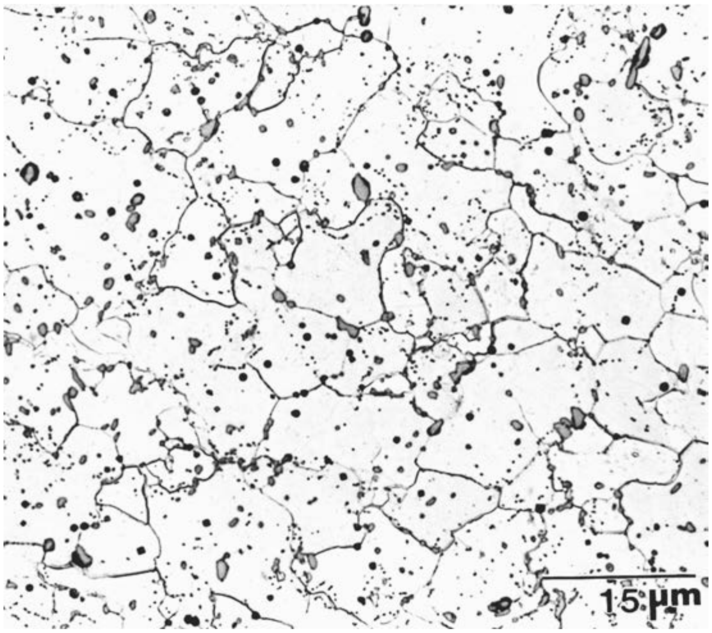

Fig. 1.13 Micrograph of AISI 430F free-machining ferritic stainless steel showing a microstructure consisting of ferrite and globular manganese sulfides (gray constituent). Etched in three parts glycerol, two parts HCl, and one part HNO_3. 750×

Wear-Resistant Steels

Tool Steels. By far the largest class of wear-resistant steels is the tool steels. There is an AISI classification system for the tool steels that has been in existence for many years. The AISI two- and three-digit codes begin with a letter representing the class of tool steel. The general classes are as follows:

Letter	Type of steel
W	Water-hardening tool steels
A	Air-hardening, medium-alloy, cold-work steels
O	Oil-hardening, cold-work steels
S	Shock-resisting steels
M	Molybdenum high-speed steels
T	Tungsten high-speed steels
H	Chromium high-speed steels
D	High-carbon, high-chromium, cold-work steels
L	Low-alloy, special-purpose tool steels
P	Low-carbon mold steels

Most all of the tool steels contain molybdenum and/or tungsten. Other alloying elements, such as vanadium, cobalt, nickel, and chromium, are also added for certain characteristics. The microstructure of a typical tool steel is shown in Fig. 1.19. A complete list of the composition ranges of the tool steels can be found in the Appendix.

Austenitic Manganese Steels . Another type of wear-resistant steel is the series of austenitic manganese steels. These steels are basically varients of Hadfield manganese steel invented in 1882 by the Englishman Sir Robert Hadfield. These steels contain between 11 and 14% Mn and between 0.7 and 1.45% C. The alloys are austenitic at room temperature and possess a unique combination of toughness and ductility coupled with high work-hardening capacity and good wear resistance. Hadfield manganese steels are widely used in applications requiring abrasion resistance, for example, ore crushers. They are classified by ASTM as grade A 128. A list of the compositional variations can be found in the Appendix. The microstructure of a typical Hadfield steel is shown in Fig. 1.20.

Special-Purpose Alloy Steels

There are a number of special-purpose steels that do not fit in any of the previous categories. These steels include the magnetic steels, the ultrahigh-strength steels, the electrical steels, and so on. In this Chapter, some of these special-purpose steels are discussed briefly.

Ultrahigh-Strength (Maraging) Steels. The maraging steels (mar-aging represents martensitic aging) can be classified as ultrahigh-strength steels. These steels develop their high strength (above 1380 MPa, or 200 ksi, yield strength) through a precipitation reaction that occurs by an aging-type heat treatment. The steels have a martensitic microstructure. The more common maraging steels contain 18% Ni, 8.5 to 10% Co, 3.3 to 5% Mo, 0.2 to 1.6% Ti, and 0.1 to 0.3% Al. Because of the high cost of cobalt, there are a number of low-cobalt and cobalt-free alloys. The composition of a number of maraging steels can be found in the Appendix. The microstructure of a typical maraging steel is shown in Fig. 1.21.

Magnetic Steels. A popular permanent (hard) magnetic steel is Alnico V, which contains 20% Co, 14% Ni, 8% Al, and 3% Cu. There are a number of high-permeability steels, such as Permal-

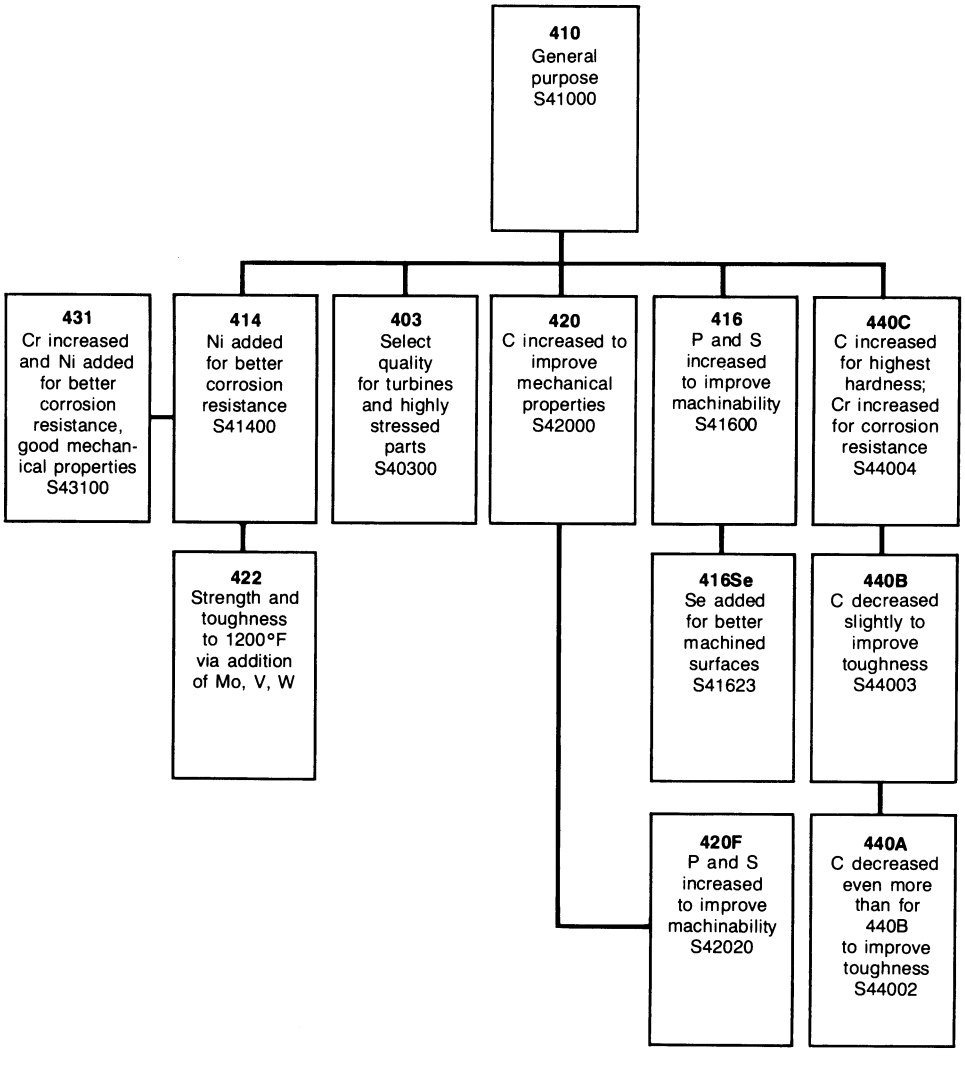

Fig. 1.14 Family relationships for standard martensitic stainless steels

loy, which contains 45% Ni, and Permendur, which contains 50% Co. All these steels have very high alloy contents.

Nonmagnetic Steels. The austenitic stainless steels and Hadfield manganese steels described previously are nonmagnetic. However, there are specific steels designed to have very low magnetic permeability. These steels usually contain 14 to 30% Mn. These steels can also be used for cryogenic (low-temperature) applications. The compositions of these steels are listed in the Appendix.

Low-Thermal-Expansion Steels. Some steels are designed to have a very low coefficient of thermal expansion. One such alloy is Invar, which contains 36% Ni. Super Invar contains 31% Ni and 4 to 6% Co and has a coefficient of thermal expansion near zero. Another low-expansion alloy, Kovar, with 29% Ni and 17% Co,

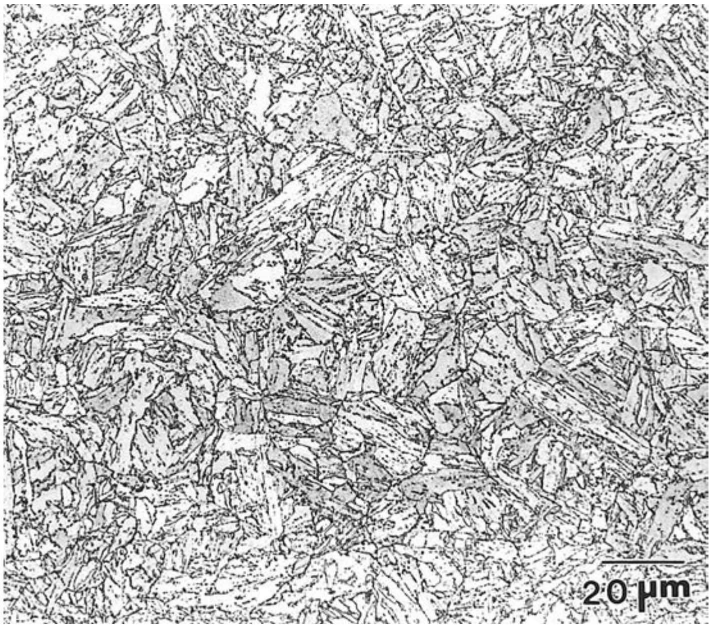

Fig. 1.15 Micrograph of AISI 410 martensitic stainless steel showing a microstructure consisting of 100% martensite. Etched in Kalling's No. 1 reagent. 500×

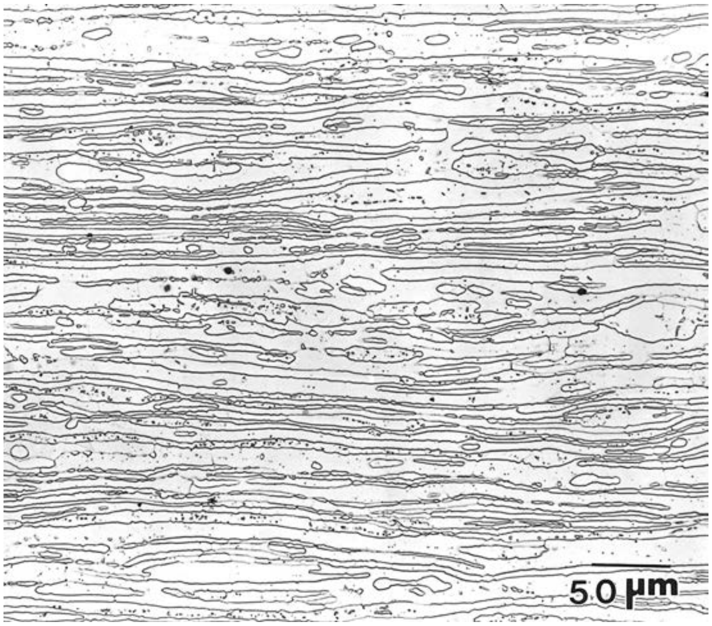

Fig. 1.16 Micrograph of a duplex stainless steel (7Mo Plus) showing a microstructure consisting of ferrite and austenite. The ferrite is the continuous matrix constituent. Electrolytically etched in 10% oxalic acid at 5 V. 200×

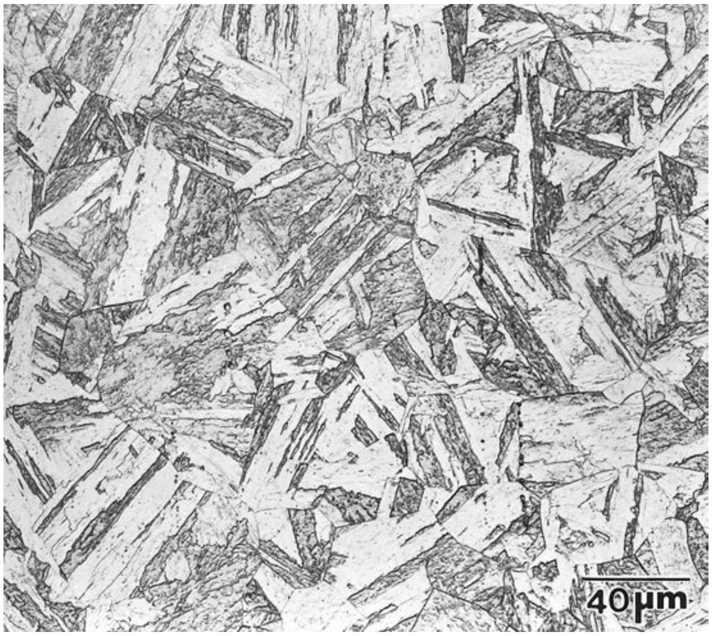

Fig. 1.17 Micrograph of a precipitation-hardening stainless steel (Custom 630) showing a microstructure consisting of martensite. Etched in Fry's reagent. 320×

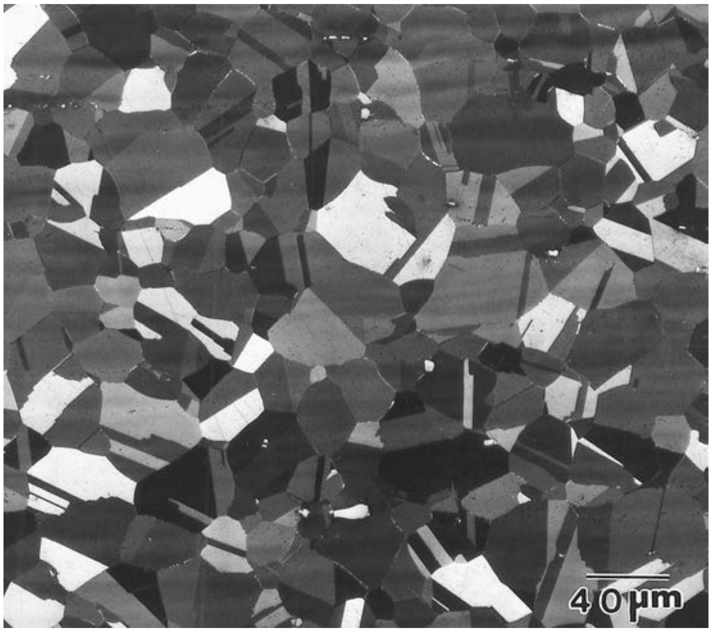

Fig. 1.18 Micrograph of an iron-base superalloy A286 showing a microstructure consisting of austenite. The straight-edged regions are annealing twins. Etched in a solution of 100 ml water, 20 ml HCl, 1 g NH_4F HF, and 0.5 g $K_2S_2O_5$. 200×

matches the coefficient of thermal expansion of glass and is used for glass-to-metal seals. The microstructure of a typical low-expansion steel is shown in Fig. 1.22.

High-Thermal-Expansion Steels. The maximum possible coefficient of thermal expansion for a steel is obtained in a steel called Hi-Span-Hi, which contains 29% Ni, 8.5% Cr, 2.4% Ti, 0.4% Mn, 0.4% Si, and 0.4% Al. High-expansion alloys are used in bimetallic strips for thermally activated switches and thermostats.

Electrical Steels. There are very-low-carbon steels that are used for transformer cores and electric motor laminations. All these steels contain silicon (sometimes they contain aluminum). The transformer steels contain 3.25 to 4% Si (some contain 4.5 to 5% Si), and the motor lamination steels contain 0.5 to 1.0% Si

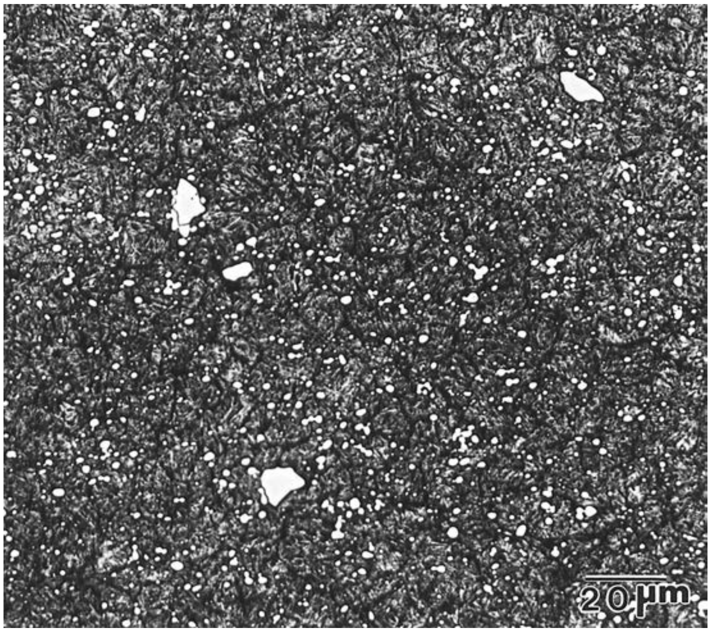

Fig. 1.19 Micrograph of AISI M-2 high-speed tool steel showing a microstructure consisting of tempered martensite and carbides (white etching constituent). Etched in 12% sodium metabisulfite solution. 500×

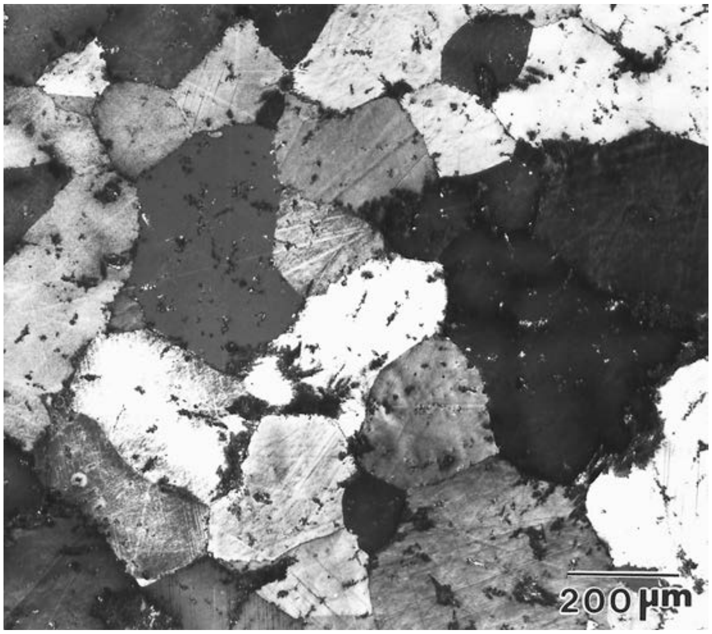

Fig. 1.20 Micrograph of ASTM A 128 austenitic manganese steel (Hadfield steel) casting showing a microstructure consisting of austenite. Etched in 2% nital (5 s) followed by removal of the stain in aqueous 3% EDTA and etching in 20% sodium metabisulfite solution. 64×

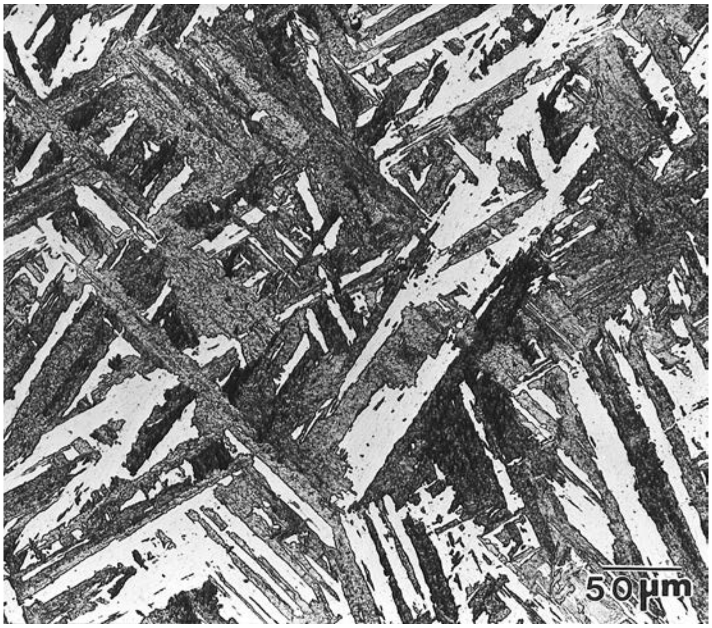

Fig. 1.21 Micrograph of a maraging steel showing a microstructure consisting of martensite. Etched in Kalling No. 1. 200×

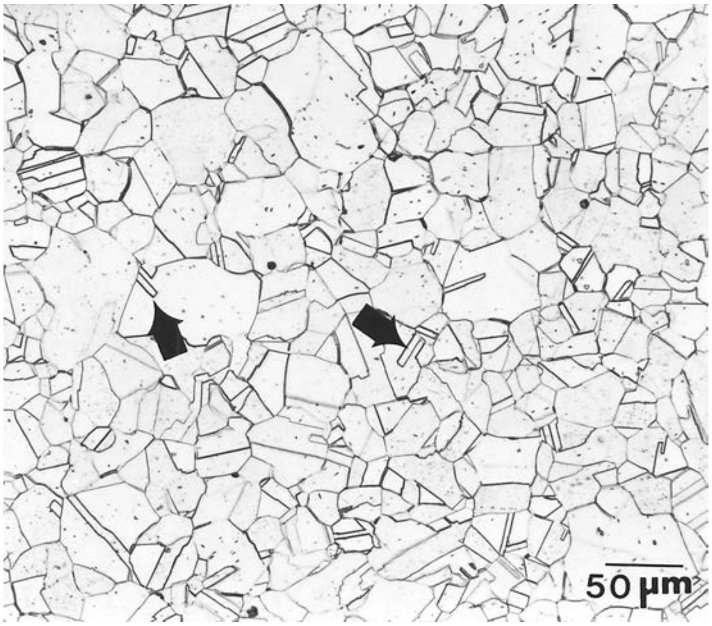

Fig. 1.22 Micrograph of a low-expansion steel (Invar) showing a microstructure consisting of austenite. The straight-edged regions (arrows) are annealing twins. Etched in 4% picral. 200×

(sometimes they also contain aluminum). Carbon is not necessary in these steels and, in fact, is considered detrimental. The microstructure of a typical motor lamination steel is shown in Fig. 1.23.

Electrical-Resistance Steels. Some steels with high electrical resistance are used for heating elements in household stoves and industrial ovens and furnaces. One such steel is Kanthal, which contains 25% Cr, 5% Al, and 3% Co. Ohmax is another steel with high resistance and is used for electrical resistors. It contains 20% Cr, 5 to 8.8% Al, and 0 to 5% Co.

Cast Irons

The cast irons generally contain more than 2% C and a variety of other alloying elements. They are classified by a rather simple, somewhat archaic system. They are classified by the appearance of their fracture surface, their microstructure, or their properties. Historically, there were two different cast irons: the cast iron that has a gray fracture appearance and the cast iron that has a white fracture appearance. Thus, the names *gray iron* and *white iron* evolved. Those irons that have a mixed gray and white appearance are called *mottled iron.* These names still apply today. Other cast irons appeared over the years and have names associated with a mechanical property, such as *malleable iron* and *ductile iron.* More recently, *compacted graphite iron* and *austempered ductile iron* have been introduced. This section examines each of these cast irons.

Gray Iron

By far the most common of all cast irons is gray iron. This iron has a gray fracture appearance, because it contains a high volume fraction of graphite flakes (the graphite flakes have a gray appearance). Gray iron is sometimes identified as "FG," which refers to the flake graphite that is present. The microstructure of a typical gray iron is shown in Fig. 1.24.

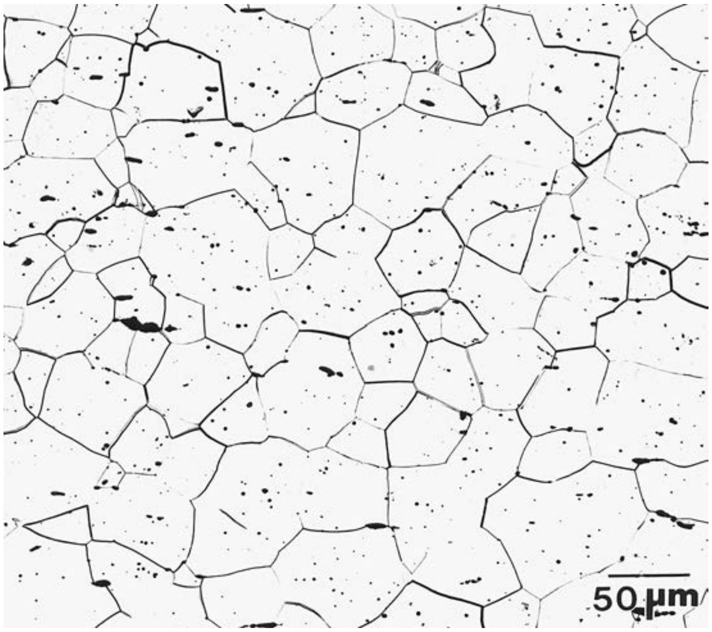

Fig. 1.23 Micrograph of a motor lamination steel showing a microstructure consisting of ferrite. Etched in 2% nital. 200×

Common unalloyed gray cast iron has the following broad range of chemical composition:

Element	Content, %
Carbon	2.5–4.0
Silicon	1.0–3.0
Manganese	0.2–1.0
Phosphorus	0.002–1.0
Sulfur	0.02–0.25

The gray irons have a high silicon content, because silicon (a graphitizer) promotes the formation of graphite during solidification. Gray iron has almost no ductility because of the presence of the graphite flakes. However, it is inexpensive and can be cast into complex shapes. The microstructure of gray iron results from a rather slow cooling rate in the casting process.

ASTM has classified the type, distribution, and size of graphite in gray iron according to specification A 247. The flake graphite patterns have been subdivided into five types, as shown in Fig. 1.25.

Each type imparts a different characteristic to the properties of the gray iron. For example, type A is preferred for most applications, because it is superior in certain wear applications. An important application is in cylinders of internal combustion engines. ASTM has also classified gray iron by a number of specifications that require certain compositional ranges and mechanical properties. A partial list follows:

ASTM designation	Type of iron
A 48	Gray iron castings
A 126	Gray iron castings for valves, flanges, and pipe fittings
A 159	Automotive gray iron castings
A 278	Gray iron castings for pressure-containing parts for temperatures up to 650 °F

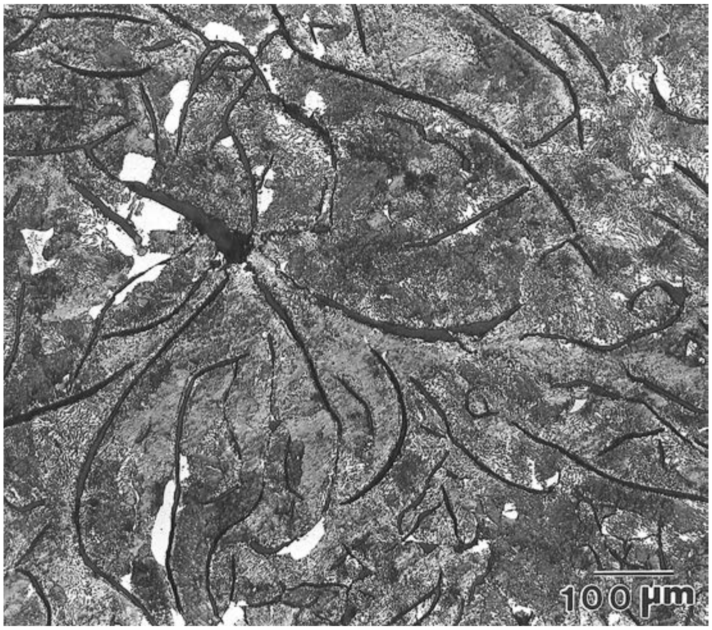

Fig. 1.24 Micrograph of a gray cast iron showing a microstructure consisting of pearlite (gray etching constituent), ferrite (light etching constituent), and graphite flakes (dark constituent). Etched in 4% picral. 100×

ASTM A 48 is the general specification for gray cast iron and classifies grades of gray iron according to minimum tensile strength in ksi, as follows:

	Minimum tensile strength	
ASTM A 48 class	**MPa**	**ksi**
Class 20	138	20
Class 25	172	25
Class 30	207	30
Class 35	241	35
Class 40	276	40
Class 45	310	45
Class 50	345	50
Class 55	379	55
Class 60	414	60

There are no compositional requirements specified in ASTM A 48.

The SAE has also classified gray iron for automotive applications by specification SAE J431. There are five grades of gray cast iron included in SAE J431, as follows:

	Minimum tensile strength	
SAE J431 grade	**MPa**	**ksi**
Grade G1800	125	18
Grade G2500	172	25
Grade G3000	207	30
Grade G3500	241	35
Grade G4000	276	40

As one can see, the grade number is linked to the minimum tensile strength in ksi, as it is in ASTM A 48, but each SAE grade has other requirements. For example, the composition and property requirements for SAE grade G1800 are as follows:

Element	Content, %
Carbon (TC) (a)	3.40–3.70
Manganese	0.50–0.80
Silicon	2.80–2.30
Phosphorus	0.15 max
Sulfur	0.15 max

(a) Carbon is expressed as total carbon (TC).

Property	Required value
Hardness, HB	187 max
Bend Properties	
Minimum transverse load, kg (lb)	780 (1720)
Minimum deflection, mm (in.)	3.6 (0.14)
Minimum tensile strength, MPa (ksi)	124 (18)

According to SAE J431, grade G1800 is used for soft iron castings (as-cast or annealed) in which strength is not a primary factor. The other higher-strength grades are used in specific automotive applications. The compositional ranges for the previously mentioned grades can be found in the Appendix.

White Iron

If a gray iron is solidified rapidly, white iron results. Graphite flakes are not present in white iron. Instead of graphite flakes, an iron carbide network forms that gives the white appearance on the fracture surface. The microstructure of a typical white iron is shown in Fig. 1.26.

The composition range of elements in unalloyed white iron are:

Element	Content, %
Carbon	1.8–3.6
Silicon	0.5–1.9
Manganese	0.25–0.8
Phosphorus	0.06–0.2
Sulfur	0.06–0.2

The silicon content is lower in white iron to minimize its graphitizing effect. White irons are extremely hard and abrasion resistant. To enhance their abrasion resistance, they are usually alloyed with nickel, chromium, and/or molybdenum. ASTM specification A 532 covers the abrasion-resistant white cast irons. There are ten different white cast irons, according to ASTM A532. These are listed subsequently:

Designation	Type of white cast iron
Class I	
Type A	Ni-Cr high-carbon
Type B	Ni-Cr low-carbon
Type C	Ni-Cr GB (grinding balls)
Type D	Nickel high-chromium
Class II	
Type A	12% Cr
Type B	15% Cr-Mo low-carbon
Type C	15% Cr-Mo high-carbon
Type D	20% Cr-Mo low-carbon
Type E	20% Cr-Mo high-carbon
Class III, type A	25% Cr

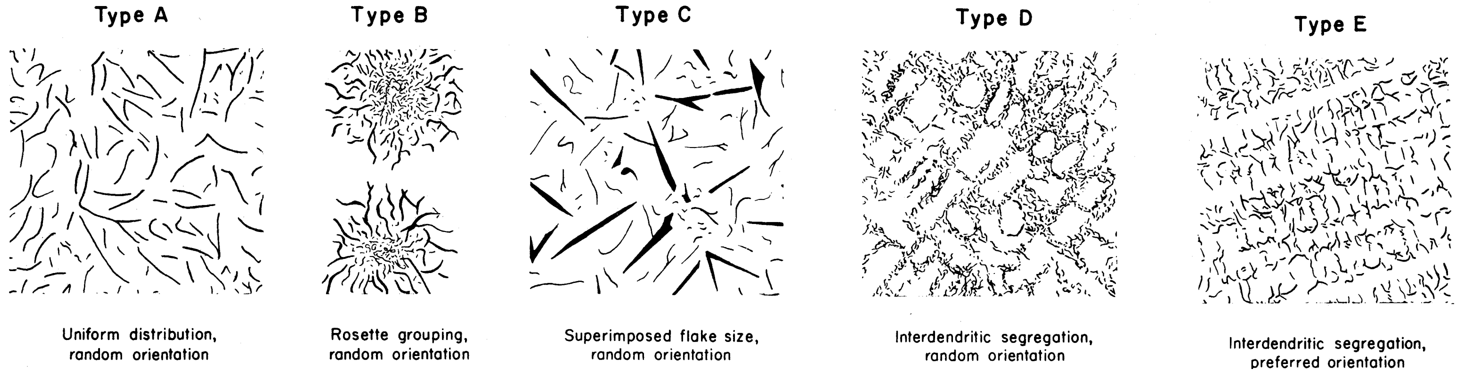
Type A — Uniform distribution, random orientation
Type B — Rosette grouping, random orientation
Type C — Superimposed flake size, random orientation
Type D — Interdendritic segregation, random orientation
Type E — Interdendritic segregation, preferred orientation

Fig. 1.25 Types of graphite flakes in gray iron (American Foundryman's Society-ASTM). In the recommended practice (ASTM A 247), these charts are shown at a magnification of 100×. They have been reduced to one-third size for reproduction here.

Mottled Iron. This type of cast iron is not intentionally produced. It results from a transition between gray and white iron in a casting and is not necessarily a desirable material. The microstructure of a mottled iron is shown in Fig. 1.27.

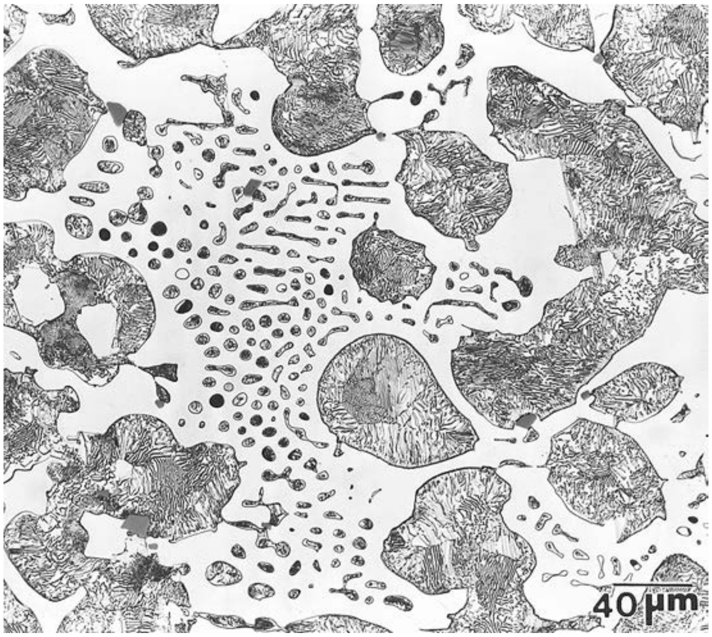

Fig. 1.26 Micrograph of a white cast iron showing a microstructure consisting of pearlite (gray etching constituent), cementite (light etching constituent), and ledeburite (regions of rounded clusters). Etched in 4% picral. 250×

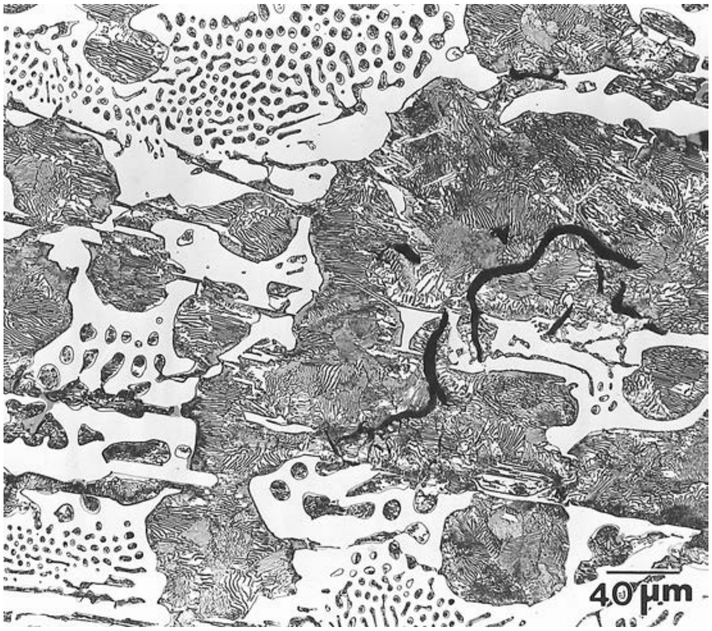

Fig. 1.27 Micrograph of a mottled cast iron showing a microstructure consisting of pearlite (dark gray etching constituent), cementite (light etching constituent), ledeburite (clusters of small, rounded pearlite particles), and graphite flakes (dark constituent). Etched in 4% picral. 250×

Malleable Iron

Malleable iron is produced by heat treating white iron to break down or decompose the iron carbide into a temper carbon (a form of graphite). Malleable iron is sometimes referred to as TG iron because of the temper graphite present. Usually, white iron is heated to 800 to 970 °C (1470 to 1780 °F) for long periods of time, on the order of 20 h. During this time, irregularly shaped nodules of graphite form. Because of the absence of the hard and brittle carbide constituent, the iron becomes malleable. The microstructure of a typical malleable iron is shown in Fig. 1.28.

The typical compositional limits of malleable iron are (wt%):

Element	Content, %
Carbon (TC) (a)	2.2–2.9
Manganese	0.2–0.6
Silicon	0.9–1.9
Sulfur	0.02–0.2
Phosphorus	0.02–0.2

(a) Carbon is expressed as total carbon, TC.

ASTM has a number of specifications for malleable iron, depending on the microstructure and application. A partial list is given subsequently:

ASTM designation	Type of malleable iron
A 47	Ferritic malleable iron castings
A 197	Cupola malleable iron
A 220	Pearlitic malleable iron castings
A 338	Malleable iron fittings and valve parts for railroad, marine, and other heavy-duty service at temperatures up to 345 °C (650 °F)
A 602	Automotive malleable iron castings

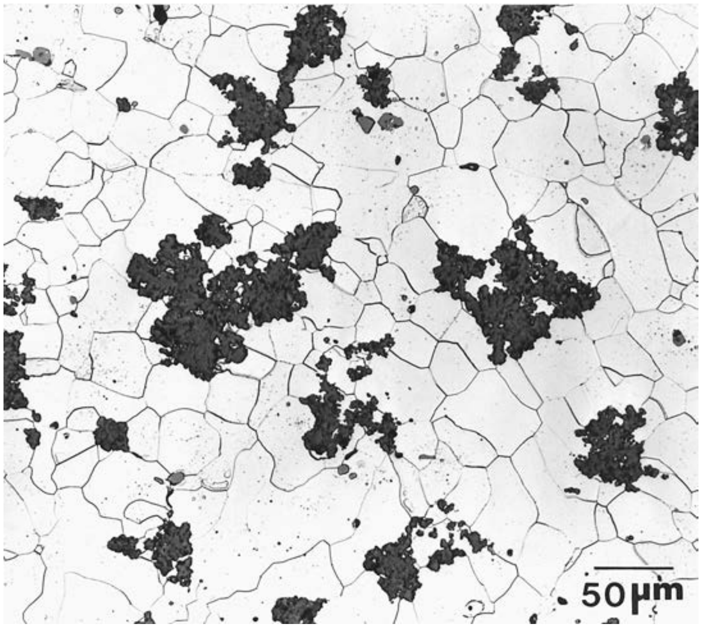

Fig. 1.28 Micrograph of a malleable cast iron showing a microstructure consisting of ferrite (light etching constituent) and temper carbon (dark gray irregular-shaped constituent). Etched in 2% nital. 200×

As an example, ASTM A 220 for pearlitic malleable iron castings has eight grades of malleable iron, depending on minimum yield strength and elongation. The class or grade code is quite unusual and incorporates the minimum yield strength and elongation levels. For example, the grades are listed subsequently:

Grade	Yield strength (min), MPa (ksi)	Tensile strength (min), MPa (ksi)	Hardness, Brinell	Elongation (min), %
40010	276 (40)	414 (60)	149–197	10
45008	310 (45)	448 (65)	156–197	8
45006	310 (45)	448 (65)	156–207	6
50005	345 (50)	483 (70)	179–229	5
60004	414 (60)	552 (80)	197–241	4
70002	383 (70)	586 (85)	217–269	3
80002	552 (80)	724 (105)	269–321	1

More details of the compositional ranges of the malleable irons can be found in the Appendix.

Ductile Iron

Ductile iron, also known as nodular iron and spheroidal graphite cast iron, is a cast iron where the graphite is in the form of spheres or nodules. The nodules are not as irregularly shaped as in malleable iron and are formed during solidification, not by heat treatment. The code SG is sometimes used to refer to the spheroidal graphite that is present in ductile iron. ASTM has classified the types of graphite shapes found in ductile cast irons and other irons. Sketches of the ASTM A 247 classification are shown in Fig. 1.29. The ductile irons contain type I graphite (type II being imperfectly formed nodular graphite). Type III would

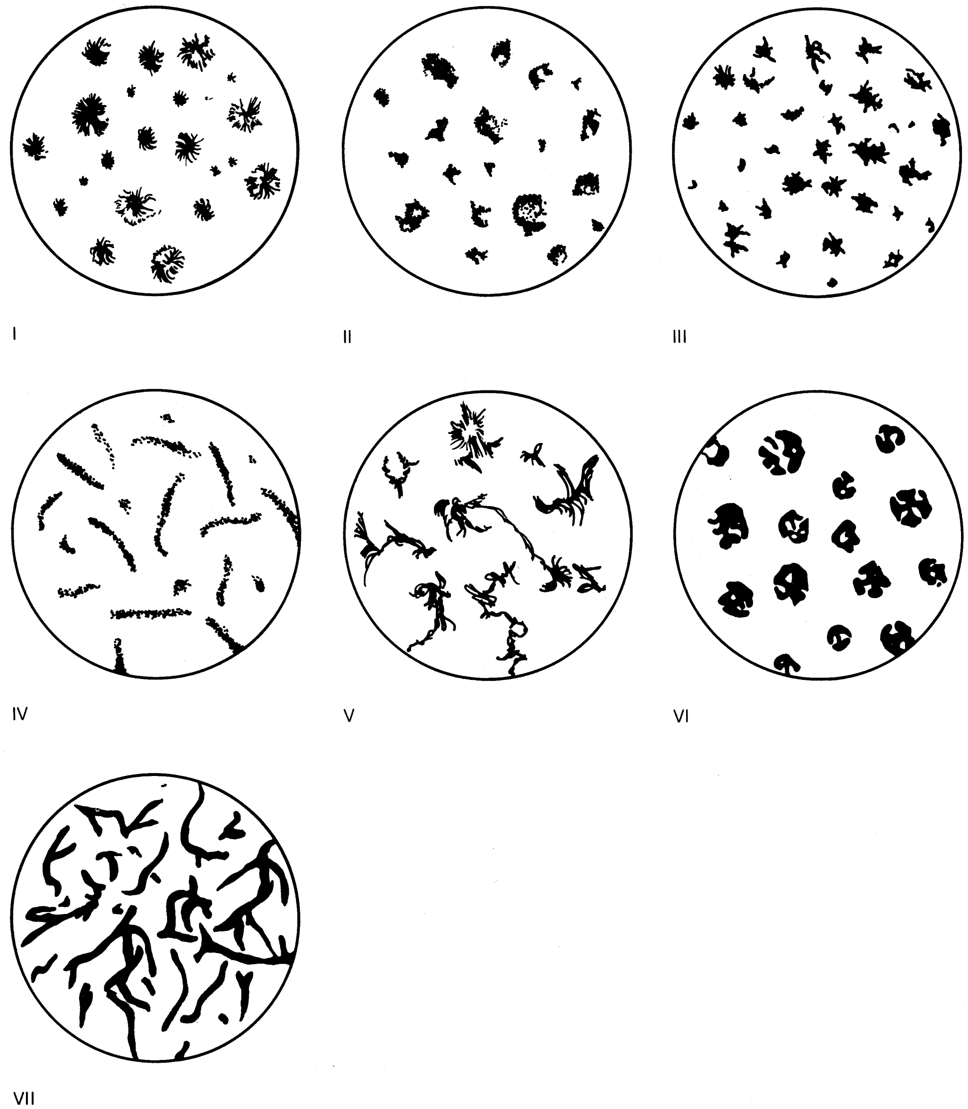

Fig. 1.29 Typical graphite shapes after ASTM A 247. I, spheroidal graphite; II, imperfect spheroidal graphite; III, temper graphite; IV, compacted graphite: V, crab graphite; VI, exploded graphite; VII, flake graphite

typify a malleable iron, type IV a compacted graphite iron (described at the end of this chapter), and type VII would typify the flake graphite of a gray iron. The microstructure of a typical ferritic ductile iron is shown in Fig. 1.30.

To produce ductile iron, a fairly high-purity cast iron is inoculated with 0.03 to 0.06% Mg or 0.005 to 0.20% Ce. These elements provide nuclei on which the graphite spheroids grow. Because of the shape of the graphite, this type of cast iron exhibits far greater ductility than gray iron.

The chemical composition limits of ductile iron are given below (wt%):

Element	Content, %
Carbon	3.0–4.0
Silicon	1.8–2.8
Manganese	0.1–1.0
Phosphorus	0.01–0.1
Sulfur	0.01–0.03

Ductile irons are classified by both ASTM and SAE according to the application and properties desired. A partial ASTM list is shown subsequently:

ASTM designation	Type of ductile iron
A 377	Ductile iron pressure pipe
A 395	Ferritic ductile iron pressure-retaining castings for use at elevated temperatures
A 439	Austenitic ductile iron castings
A 476	Ductile iron castings for paper mill dryer rolls
A 536	Ductile iron castings
A 716	Ductile iron culvert pipe

A look at ASTM A 536 shows that five grades are defined according to minimum tensile strength, minimum yield strength, and elongation. In fact, the grade code number incorporates all three properties, as follows:

Grade	Tensile strength (min), MPa (ksi)	Yield strength (min), MPa (ksi)	Elongation (min), %
60-40-18	415 (60)	276 (40)	18
60-42-10	415 (60)	290 (42)	10
65-45-12	448 (65)	310 (45)	12
70-50-05	485 (70)	345 (50)	5
80-55-06	555 (80)	379 (55)	6
80-60-03	555 (80)	415 (60)	3
100-70-03	689 (100)	485 (70)	3
120-90-02	827 (120)	621 (90)	2

To attain these various properties, the matrix microstructure varies from ferritic for the lower strengths, to pearlitic for the intermediate strengths, to martensitic for the higher strengths. Further details on the composition of ductile irons can be found in the Appendix.

Austempered Ductile Iron. This is essentially a subclass of ductile iron. Austempered ductile irons have the same spherical or nodular graphite as a normal ductile iron, but the matrix is a combination of bainite (acicular ferrite and carbides) and stabilized austenite. The microstructure of a typical austempered ductile iron is shown in Fig. 1.31. The microstructure is obtained by a special heat treatment called austempering. The heat treatment involves austenitizing, followed by a quench and an isothermal hold at a specific temperature (usually obtained by quenching

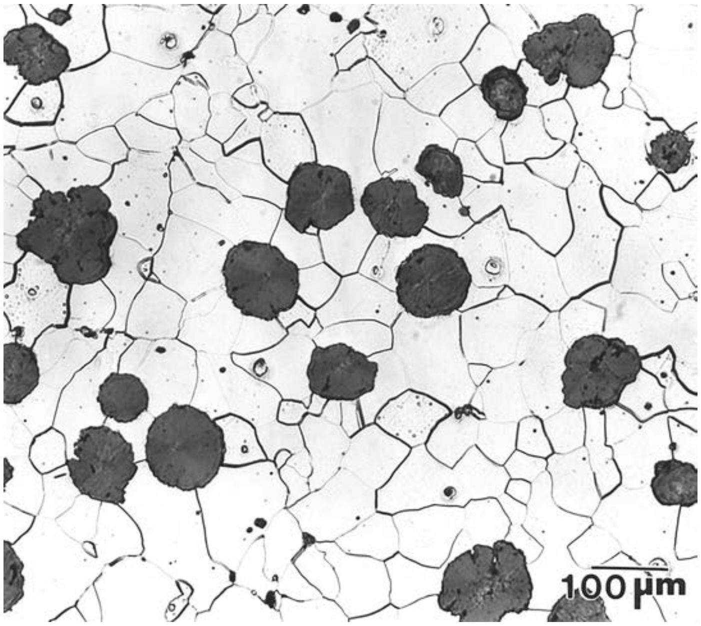

Fig. 1.30 Micrograph of a ferritic ductile (nodular) cast iron showing a microstructure consisting of ferrite (light etching constituent) and graphite nodules (dark gray constituent). Etched in 2% nital. 100×

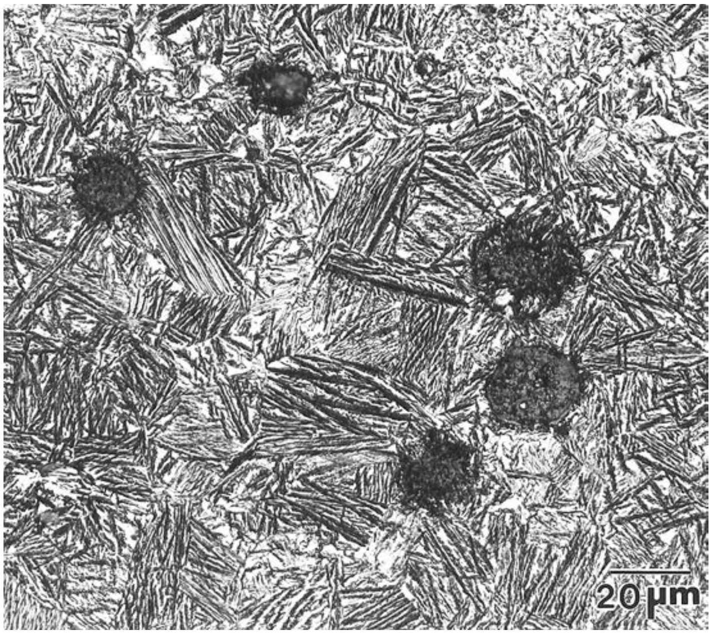

Fig. 1.31 Micrograph of an austempered ductile cast iron showing a microstructure consisting of bainite (acicular constituent) and graphite nodules (dark gray constituent). Etched in 2% nital. 500×

into a molten salt bath). ASTM has recently established a specification, A 895, for austempered ductile iron. The specification consists of five grades that incorporate the minimum tensile strength, minimum yield strength, and elongation (similar to the system discussed previously for ductile iron). ASTM A 895 has the following property requirements:

Grade	Tensile strength (min), MPa (ksi)	Yield strength (min), MPa (ksi)	Elongation (min), %	Hardness, HB	Impact energy, J (ft · lbf)
125-80-10	862 (125)	552 (80)	10	269–321	102 (75)
150-100-7	1034 (150)	690 (100)	10	302–363	81 (60)
175-125-4	1207 (175)	862 (125)	4	341–444	61 (45)
200-155-1	1379 (200)	1069 (155)	1	388–477	34 (25)
230-185	1586 (230)	1276 (185)	. . .	444–555	. . .

Note the much higher strength levels attained in austempered ductile iron compared with all the other irons described previously. Applications for austempered ductile iron include gears, automotive crankshafts and universal joints, and other parts requiring wear resistance, and high fatigue and impact strength.

Compacted Graphite Iron

Compacted graphite cast iron has a graphite shape somewhere between the flake graphite found in gray cast iron and the nodular graphite found in ductile iron. Thus, the properties of compacted graphite cast irons are in-between those of gray and ductile iron. Compacted graphite appears as short, thick flakes similar to type IV shown in Figure 1.29. The iron is also referred to as CG iron because of the presence of compacted graphite. The shape of the graphite is controlled by the addition of minor alloying elements, such as magnesium, titanium, calcium, cerium, and/or aluminum. The basic compositional range of standard elements is as follows (wt%):

Element	Content, %
Carbon	2.4–4.0
Silicon	1.0–3.0
Manganese	0.2–1.0
Phosphorus	0.01–0.10
Sulfur	0.01–0.03

The basic range of composition is similiar to ductile iron, described previously. Currently, there are no ASTM or SAE specifications for compacted graphite cast irons. One of the largest applications for compacted graphite cast iron is in the manufacture of ingot molds, where the mold life can be extended by 20 to 70% over the life of molds made from normal gray cast iron.

Chapter 1: Introduction to Steels and Cast Irons

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