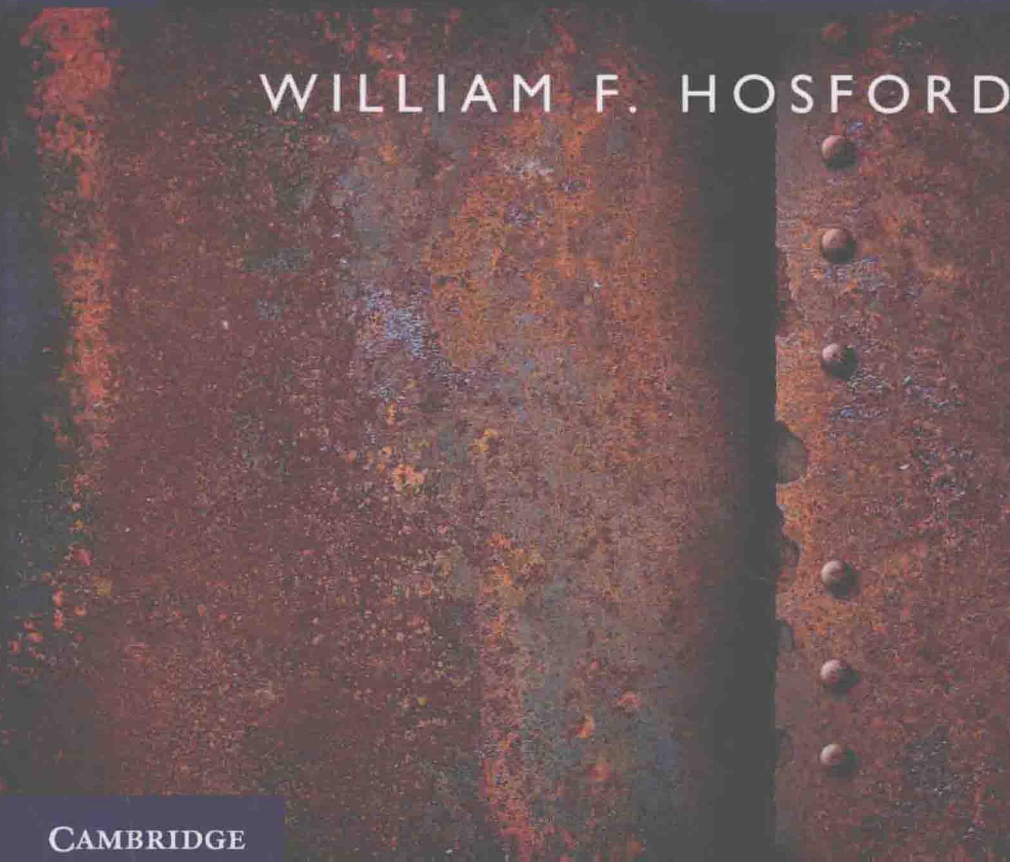
IRON AND STEEL

WILLIAM F. HOSFORD



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Iron and Steel

Modern civilization as we know it would not be possible without iron and steel. Steel is essential in the machinery necessary for the manufacture of all our needs. Even the words themselves have come to suggest strength. Phrases such as *iron willed*, *iron fisted*, *iron clad*, *iron curtain*, and *pumping iron* imply strength. A *steely glance* is a stern look. A *heart of steel* refers to a very hard demeanor. The Russian dictator Stalin (which means "steel" in Russian) chose the name to invoke fear in his subordinates. This book is intended both as a resource for engineers and as an introduction to the layman about our most important metal system. After an introduction that deals with the history and refining of iron and steel, the rest of the book examines their physical properties and metallurgy.

William F. Hosford is Professor Emeritus of Materials Science at the University of Michigan. He is the author of numerous research publications and the following books: *The Mechanics of Crystals and Textured Polycrystals* (1993); *Physical Metallurgy* (2005); *Materials Science: An Intermediate Text* (2007); *Materials for Engineers* (2008); *Reporting Results: A Practical Guide for Scientists and Engineers* with David C. Van Aken (2008); *Mechanical Behavior of Materials*, 2nd edition (2009); *Wilderness Canoe Tripping* (2009); *Solid Mechanics* (2010); *Physical Metallurgy*, 2nd edition (2010); and *Metal Forming: Mechanics and Metallurgy*, 4th edition, with Robert M. Caddell (2011).

PREFACE

Modern civilization would not be possible without iron and steel. Steel is an essential component of all machinery used for manufacture of all our goods. The words *iron* and *steel* have come to suggest strength as evident in the following terms: *iron willed*, *iron fisted*, *iron clad*, *iron curtain*, and *pumping iron*. A *steely glance* is a stern look. A *heart of steel* implies a very hard demeanor. The Russian dictator Joseph Stalin (which means "steel" in Russian) chose that name to invoke fear in his subordinates.

This book is intended both as a resource for engineers and as an introduction to the layman to our most important metal system. The first few chapters cover the history and refining of iron and steel; the rest of the book covers physical properties and physical metallurgy.

I have drawn heavily on material from *Physical Metallurgy of Steels* by W. C. Leslie and *Steel Metallurgy for the Nonmetallurgist* by J. D. Verhoeven. However, this book includes material not covered in either of those.

Professors Robert Pehlke, Ronald Gibala, John Keough, and Paul Trojan were very helpful. Kathy Hayrynen supplied a number of micrographs.

The reader is assumed to have had a course in materials science and to be familiar with phase diagrams, Fick's laws of diffusion, and the concept of free energy.

CONTENTS

1

GENERAL INTRODUCTION

NOMENCLATURE

The terms *iron* and *steel* are often confusing to the general public. *Iron* is an element (26 on the periodic table). The word *iron* comes from the Scandinavian word *iarn*. The chemical symbol *Fe* comes from the Latin word for iron, *ferrum*. The French word for iron is *fer*, the German word, *Eisen*. The Dutch word is *ijzeret*, and the Spanish is *hierro*.

The word *steel* is used to describe almost all alloys of iron. It is often said that steel is an alloy of iron and carbon. However, many steels contain almost no carbon. Carbon contents of some steels are as low as 0.002% by weight. The most widely used steels are low-carbon steels that have less than 0.06% carbon. Low-carbon steels are used for automobile bodies, appliances, cans, and cabinets. Higher carbon contents are used in steel with higher strengths. Tools are made from steels containing up to about 1.2% carbon.

The Sanskrit word for steel is *stakati*. The German word is *Stahl*; the Russian, *stalin*; the French, *acier*; the Spanish, *acero*; and the Dutch, *staal*. *Chalybs* is the Latin word for steel.

Wrought iron was an iron-based product with entrapped slag stringers that contained very little carbon. It is no longer produced, having been replaced by much cheaper low-carbon steel. The term *wrought iron* is still applied to garden furniture and similar products that are made today from low-carbon steel.

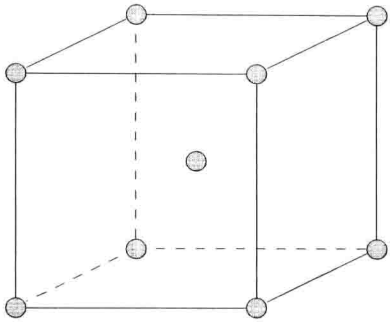

Figure 1.1. Unit cell of a body-centered cubic crystal.

Cast irons are iron-based alloys that contain 2.5 to 4% carbon and 2 to 3% silicon. In white cast iron, the carbon is present as iron carbide, whereas in gray and ductile cast irons, most of the carbon is present as graphite.

PHASES

Pure iron undergoes several phase changes. Above 1538°C, it is liquid. On cooling below 1538°C, it transforms to a body-centered cubic (bcc) structure, delta (δ)-ferrite, as shown in Figure 1.1.

On further cooling, it transforms to a denser face-centered cubic (fcc) structure, gamma (γ)-austenite, at 1400°C (Figure 1.2).

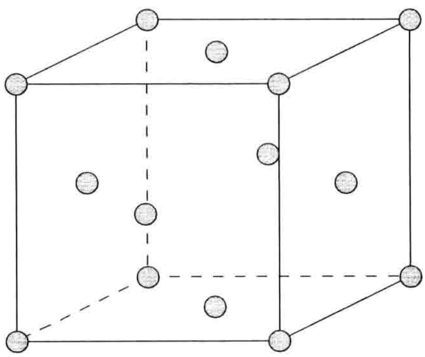

Figure 1.2. Unit cell of a face-centered cubic crystal.

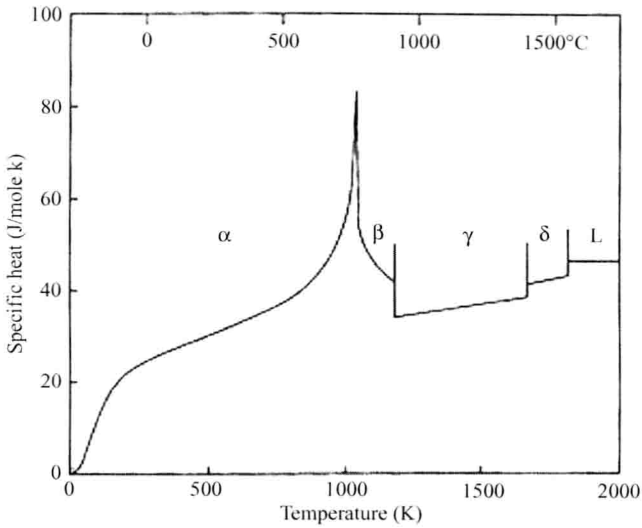

Figure 1.3. Temperature dependence of the specific heat of iron.

Below 911°C, it transforms back to bcc α-ferrite (which is the same as δ-ferrite). There is a paramagnetic-to-ferromagnetic transformation at the Curie temperature (770°C). Early researchers mistook a peak in the specific heat as a latent heat of transformation (Figure 1.3) and designated the structure between 770°C and 911°C as β-iron.

Physical properties of iron are listed in Appendix I.

PRODUCTION

The production of iron is very much greater than other metals. In the U.S. the annual tonnage of iron and steel is almost 40 times as great as that of aluminum and almost 65 times greater than the production of copper. Recycling accounts for over 80% of the steel.

2

EARLY HISTORY OF IRON AND STEEL

NATIVE IRON

The only sources of iron available to early humans were meteoric iron and native (telluric) iron. Both were scarce. Most meteorites are non-metallic; only about 6% are iron, and these contain about 7 to 15% nickel. In 1808, William Thomson sectioned and etched a meteorite, noting the remarkable patterns. Although he published his findings in 1808, they attracted little interest. Also in 1808, an Austrian, Alois von Widmannstätten, also etched a meteorite and observed the structure that is now known by his name. In 1820, he and Carl von Schreibers published a book on meteorites, which contained a print from a heavily etched meteorite (Figure 2.1). Native iron is even scarcer, being limited to small particles in western Greenland. Archeological finds of iron with considerable amounts of nickel suggest that they were made from meteorites.

The first production of iron dates back to at least 2000 BC in India and Sri Lanka. By 1200 BC, production of iron was widespread in China and the Near East. The most common iron ores are hematite (Fe_2O_3) and magnetite (Fe_3O_4). Smelting of iron involved heating iron ore (oxides of iron) with charcoal. The reaction of iron oxide with carbon produced carbon monoxide and carbon dioxide. The air was supplied by either a natural draft or some means of blowing. Early furnaces were of various types. An open-pit furnace is shown

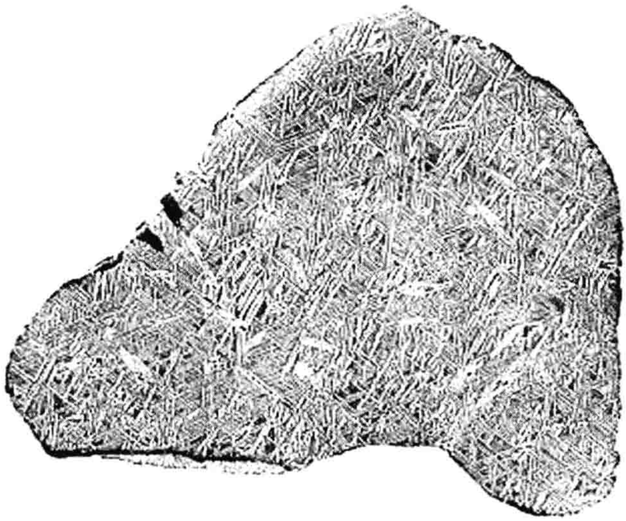

Figure 2.1. The imprint from an iron meteorite heavily etched by Widmannstätten.

in Figure 2.2. The carbon content of iron produced in pit furnaces was usually low because of the low temperatures achieved and resulted in semisolid sponge.

With shaft furnaces (Figure 2.3), the higher temperatures resulted in higher carbon contents. In the furnaces, charcoal reacted with the air to form carbon monoxide, which reduced some of the ore. The resulting carbon dioxide reacted with charcoal to form more carbon monoxide.

The product of the lower-temperature furnaces was low in carbon and much like wrought iron. It was soft and formable. If heated in

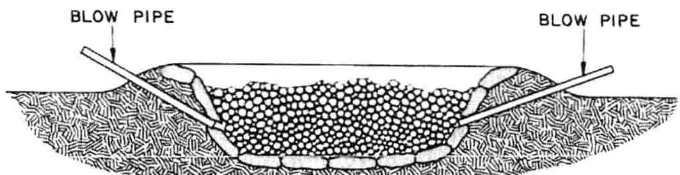

Figure 2.2. An early open-pit iron furnace. From *The Making, Shaping and Treating of Steel*, 9th ed. U.S. Steel Co. (1971).

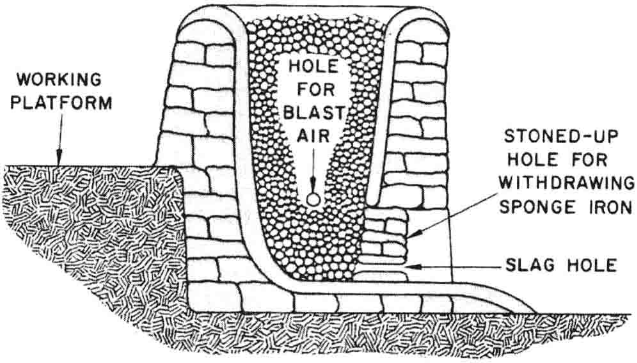

Figure 2.3. An early shaft-type iron furnace. From *The Making, Shaping and Treating of Steel*, ibid.

charcoal, it would absorb more carbon and could be made into useful steel tools. The higher-temperature furnaces produced molten iron that contained up to 4% carbon. After it solidified, it formed a brittle material that was at first discarded. Later it was learned that the carbon content could be reduced by remelting in contact with air. By 200 BC, the Chinese had started casting the high-carbon material into useful objects.

WROUGHT IRON

There is a wrought-iron pillar in Delhi, India, that dates back to at least the late fourth century. It is more than 7 m in height and has resisted corrosion over the many centuries. Wrought iron is the principal material in the Eiffel Tower, constructed in 1887.

After about AD 1300, wrought iron was produced in a Catalan furnace (Figure 2.4). The resulting semisolid product was pried out and hammered into bars. The American bloomery was a modification of this process, differing in that the charge of ore and charcoal were mixed together, and waterpower was used to create the blast.

The microstructure of wrought iron is shown in Figure 2.5, together with a typical fracture. Before the introduction of cheap