

MECHANICAL ENGINEERS' HANDBOOK

Materials and Engineering
Mechanics » Volume
1

MYER KUTZ EDITOR

FOURTH EDITION

WILEY

Mechanical Engineers' Handbook

To Sol, Dorothy, and Jeanne, in Blessed Memory

Preface

The first volume of the fourth edition of the *Mechanical Engineers' Handbook* is comprised of two major parts. The first part, Materials, has 15 chapters. All of them appeared in the third edition; 10 have been updated for this new edition. They cover metals, plastics, composites, ceramics, smart materials, and electronic materials and packaging. The metals covered are carbon, alloy, and stainless steels; aluminum and aluminum alloys; copper and copper alloys; titanium alloys; nickel and its alloys; magnesium and its alloys; and superalloys. The intent in all of the materials chapters is to provide readers with expert advice on how particular materials are typically used and what criteria make them suitable for specific purposes. This part of Volume I concludes with a chapter on sources of materials data, the intent being to provide readers with guidance on finding reliable information on materials properties, in addition to those that can be found in this volume, and a chapter on analytical methods of materials selection, which is intended to give readers techniques for specifying which materials might be suitable for particular applications.

The second part of Volume 1, Engineering Mechanics, has 12 chapters, half of them new to the handbook. They cover a broad range of topics, including the fundamentals of stress analysis (this chapter, in the handbook since the first edition in 1986, has been updated for the first time), force measurement (new), strain measurement (new), the finite-element method, viscosity measurement (new), tribology measurements (new), vibration and shock (updated from the third edition), acoustics (new), and acoustics measurements (new). There is a three-chapter section on methodologies that engineers use to predict failures with three major classes of materials—metals, plastics, and ceramics (all three chapters have been updated). I have removed the chapter on lubrication of machine elements, which had been unchanged since the first edition in 1986. I was unable through the years and handbook editions to get anyone to update the chapter. The material is too old by now and many of the references can no longer be accessed (some of the organizations that developed referenced materials have simply disappeared). The chapters on viscosity and tribology measurements serve as replacements. The chapters on acoustics and acoustics measurements replace the chapter, Noise Measurements and Control, which had been unchanged since the first edition.

Chapters from the mechanical design section, formerly in this volume, have been moved to Volumes 2 and 3, with the exception of the chapter on electronic materials and packaging. Prefaces to those volumes provide further details on the move.

Contributors of the chapters in Volume I include professors, engineers working in industry, and consultants, mainly from North America, but also from Egypt, the Netherlands, the United Kingdom, Germany, and India. I would like to thank all of them for the considerable time and effort they put into preparing their chapters.

Vision for the Fourth Edition

Basic engineering disciplines are not static, no matter how old and well established they are. The field of mechanical engineering is no exception. Movement within this broadly based discipline is multidimensional. Even the classic subjects, on which the discipline was founded, such as mechanics of materials and heat transfer, keep evolving. Mechanical engineers continue to be heavily involved with disciplines allied to mechanical engineering, such as industrial and manufacturing engineering, which are also constantly evolving. Advances in other major disciplines, such as electrical and electronics engineering, have significant impact on the work of mechanical engineers. New subject areas, such as neural networks, suddenly become all the rage.

In response to this exciting, dynamic atmosphere, the Mechanical Engineers' Handbook expanded dramatically, from one to four volumes for the third edition, published in November 2005. It not only incorporated updates and revisions to chapters in the second edition, published seven years earlier, but also added 24 chapters on entirely new subjects, with updates and revisions to chapters in the Handbook of Materials Selection, published in 2002, as well as to chapters in Instrumentation and Control, edited by Chester Nachtigal and published in 1990, but never updated by him.

The fourth edition retains the four-volume format, but there are several additional major changes. The second part of Volume I is now devoted entirely to topics in engineering mechanics, with the addition of five practical chapters on measurements from the Handbook of Measurement in Science and Engineering, published in 2013, and a chapter from the fifth edition of Eshbach's Handbook of Engineering Fundamentals, published in 2009. Chapters on mechanical design have been moved from Volume I to Volumes II and III. They have been augmented with four chapters (updated as needed) from Environmentally Conscious Mechanical Design, published in 2007. These chapters, together with five chapters (updated as needed, three from Environmentally Conscious Manufacturing, published in 2007, and two from Environmentally Conscious Materials Handling, published in 2009) in the beefed-up manufacturing section of Volume III, give the handbook greater and practical emphasis on the vital issue of sustainability.

Prefaces to the handbook's individual volumes provide further details on chapter additions, updates and replacements. The four volumes of the fourth edition are arranged as follows:

Volume 1: Materials and Engineering Mechanics—27 chapters

Part 1. Materials—15 chapters

Part 2. Engineering Mechanics—12 chapters

Volume 2: Design, Instrumentation and Controls—25 chapters

Part 1. Mechanical Design—14 chapters

Part 2. Instrumentation, Systems, Controls and MEMS —11 chapters

Volume 3: Manufacturing and Management—28 chapters

Part 1. Manufacturing—16 chapters

Part 2. Management, Finance, Quality, Law, and Research—12 chapters

Volume 4: Energy and Power—35 chapters

Part 1: Energy—16 chapters

Part 2: Power—19 chapters

The mechanical engineering literature is extensive and has been so for a considerable period of time. Many textbooks, reference works, and manuals as well as a substantial number of journals exist. Numerous commercial publishers and professional societies, particularly in the United States and Europe, distribute these materials. The literature grows continuously, as applied mechanical engineering research finds new ways of designing, controlling, measuring, making, and maintaining things, as well as monitoring and evaluating technologies, infrastructures, and systems.

Most professional-level mechanical engineering publications tend to be specialized, directed to the specific needs of particular groups of practitioners. Overall, however, the mechanical engineering audience is broad and multidisciplinary. Practitioners work in a variety of organizations, including institutions of higher learning, design, manufacturing, and consulting firms, as well as federal, state, and local government agencies. A rationale for a general mechanical engineering handbook is that every practitioner, researcher, and bureaucrat cannot be an expert on every topic, especially in so broad and multidisciplinary a field, and may need an authoritative professional summary of a subject with which he or she is not intimately familiar.

Starting with the first edition, published in 1986, my intention has always been that the Mechanical Engineers' Handbook stand at the intersection of textbooks, research papers, and design manuals. For example, I want the handbook to help young engineers move from the college classroom to the professional office and laboratory where they may have to deal with issues and problems in areas they have not studied extensively in school.

With this fourth edition, I have continued to produce a practical reference for the mechanical engineer who is seeking to answer a question, solve a problem, reduce a cost, or improve a system or facility. The handbook is not a research monograph. Its chapters offer design techniques, illustrate successful applications, or provide guidelines to improving performance, life expectancy, effectiveness, or usefulness of parts, assemblies, and systems. The purpose is to show readers what options are available in a particular situation and which option they might choose to solve problems at hand.

The aim of this handbook is to serve as a source of practical advice to readers. I hope that the handbook will be the first information resource a practicing engineer consults when faced with a new problem or opportunity—even before turning to other print sources, even officially sanctioned ones, or to sites on the Internet. In each chapter, the reader should feel that he or she is in the hands of an experienced consultant who is providing sensible advice that can lead to beneficial action and results.

Can a single handbook, even spread out over four volumes, cover this broad, interdisciplinary field? I have designed the Mechanical Engineers' Handbook as if it were serving as a core for an Internet-based information source. Many chapters in the handbook point readers to information sources on the Web dealing with the subjects addressed. Furthermore, where appropriate, enough analytical techniques and data are provided to allow the reader to employ a preliminary approach to solving problems.

The contributors have written, to the extent their backgrounds and capabilities make possible, in a style that reflects practical discussion informed by real-world experience. I would like readers to feel that they are in the presence of experienced teachers and consultants who know about the multiplicity of technical issues that impinge on any topic within mechanical engineering. At the same time, the level is such that students and recent graduates can find the handbook as accessible as experienced engineers.

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PART 1

MATERIALS

CHAPTER 1

CARBON AND ALLOY STEELS

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1 INTRODUCTION

Steel is the most common and widely used metallic material in today's society. It can be cast or wrought into numerous forms and can be produced with tensile strengths exceeding 5 GPa. A prime example of the versatility of steel is in the automobile where it is the material of choice and accounts for over 60% of the weight of the vehicle. Steel is highly formable as seen in the contours of the automobile outerbody. Steel is strong and is used in the body frame, motor brackets, driveshaft, and door impact beams of the vehicle. Steel is corrosion resistant when coated with the various zinc-based coatings available today. Steel is dent resistant when compared with other materials and provides exceptional energy absorption in a vehicle collision. Steel is recycled and easily separated from other materials by a magnet. Steel is inexpensive compared with other competing materials such as aluminum and various polymeric materials.

In the past, steel has been described as an alloy of iron and carbon. Today, this description is no longer applicable since in some very important steels, e.g., interstitial-free (IF) steels and type 409 ferritic stainless steels, carbon is considered an impurity and is present in quantities of only a few parts per million. By definition, steel must be at least 50% iron and must contain one or more alloying elements. These elements generally include carbon, manganese, silicon, nickel, chromium, molybdenum, vanadium, titanium, niobium, and aluminum. Each chemical element has a specific role to play in the steelmaking process or in achieving particular properties or characteristics, e.g., strength, hardness, corrosion resistance, magnetic permeability, and machinability.

Reprinted from *Handbook of Materials Selection*, Wiley, New York, 2002, by permission of the publisher.

2 STEEL MANUFACTURE

In most of the world, steel is manufactured by integrated steel facilities that produce steel from basic raw materials, i.e., iron ore, coke, and limestone. However, the fastest growing segment of the steel industry is the “minimill” that melts steel scrap as the raw material. Both types of facilities produce a wide variety of steel forms, including sheet, plate, structural, railroad rail, and bar products.

Ironmaking. When making steel from iron ore, a blast furnace chemically reduces the ore (iron oxide) with carbon in the form of coke. Coke is a spongelike carbon mass that is produced from coal by heating the coal to expel the organic matter and gases. Limestone (calcium carbonate) is added as a flux for easier melting and slag formation. The slag, which floats atop the molten iron, absorbs many of the unwanted impurities. The blast furnace is essentially a tall hollow cylindrical structure with a steel outer shell lined on the inside with special refractory and graphite brick. The crushed or pelletized ore, coke, and limestone are added as layers through an opening at the top of the furnace, and chemical reduction takes place with the aid of a blast of preheated air entering near the bottom of the furnace (an area called the bosh). The air is blown into the furnace through a number of water-cooled copper nozzles called tuyeres. The reduced liquid iron fills the bottom of the furnace and is tapped from the furnace at specified intervals of time. The product of the furnace is called pig iron because in the early days the molten iron was drawn from the furnace and cast directly into branched mold configurations on the cast house floor. The central branch of iron leading from the furnace was called the “sow” and the side branches were called “pigs.” Today the vast majority of pig iron is poured directly from the furnace into a refractory-lined vessel (submarine car) and transported in liquid form to a basic oxygen furnace (BOF) for refinement into steel.

Steelmaking. In the BOF, liquid pig iron comprises the main charge. Steel scrap is added to dilute the carbon and other impurities in the pig iron. Oxygen gas is blown into the vessel by means of a top lance submerged below the liquid surface. The oxygen interacts with the molten pig iron to oxidize undesirable elements. These elements include excess carbon (because of the coke used in the blast furnace, pig iron contains over 2% carbon), manganese, and silicon from the ore and limestone and other impurities like sulfur and phosphorus. While in the BOF, the liquid metal is chemically analyzed to determine the level of carbon and impurity removal. When ready, the BOF is tilted and the liquid steel is poured into a refractory-lined ladle. While in the ladle, certain alloying elements can be added to the steel to produce the desired chemical composition. This process takes place in a ladle treatment station or ladle furnace where the steel is maintained at a particular temperature by external heat from electrodes in the lid placed on the ladle. After the desired chemical composition is achieved, the ladle can be placed in a vacuum chamber to remove undesirable gases such as hydrogen and oxygen. This process is called degassing and is used for higher quality steel products such as railroad rail, sheet, plate, bar, and forged products. Stainless steel grades are usually produced in an induction or electric arc furnace, sometimes under vacuum. To refine stainless steel, the argon–oxygen decarburization (AOD) process is used. In the AOD, an argon–oxygen gas mixture is injected through the molten steel to remove carbon without a substantial loss of chromium (the main element in stainless steel).

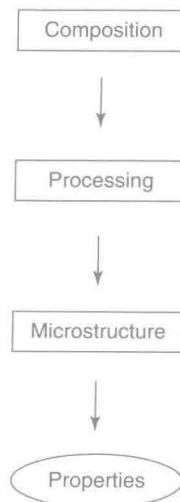
Continuous Casting. Today, most steel is cast into solid form in a continuous-casting (also called strand casting) machine. Here, the liquid begins solidification in a water-cooled copper mold while the steel billet, slab, or bloom is withdrawn from the bottom of the mold. The partially solidified shape is continuously withdrawn from the machine and cut to length for

further processing. The continuous-casting process can proceed for days or weeks as ladle after ladle of molten steel feeds the casting machine. Some steels are not continuously cast but are poured into individual cast iron molds to form an ingot that is later reduced in size by forging or a rolling process to some other shape. Since the continuous-casting process offers substantial economic and quality advantages over ingot casting, most steel in the world is produced by continuous casting.

Rolling/Forging. Once cast into billet, slab, or bloom form, the steel is hot rolled through a series of rolling mills or squeezed/hammered by forging to produce the final shape. To form hot-rolled sheet, a 50–300-mm-thick slab is reduced to final thickness, e.g., 2 mm, in one or more roughing stands followed by a series of six or seven finishing stands. To obtain thinner steel sheet, e.g., 0.5 mm, the hot-rolled sheet must be pickled in acid to remove the iron oxide scale and further cold rolled in a series of rolling stands called a tandem mill. Because the cold-rolling process produces a hard sheet with little ductility, it is annealed either by batch annealing or continuous annealing. New casting technology is emerging where thin sheets (under 1 mm) can be directly cast from the liquid through water-cooled, rotating rolls that act as a mold as in continuous casting. This new process eliminates many of the steps in conventional hot-rolled sheet processing. Plate steels are produced by hot rolling a slab in a reversing roughing mill and a reversing finishing mill. Steel for railway rails is hot rolled from a bloom in a blooming mill, a roughing mill, and one or more finishing mills. Steel bars are produced from a heated billet that is hot rolled in a series of roughing and finishing mills. Forged steels are produced from an ingot that is heated to forging temperature and squeezed or hammered in a hydraulic press or drop forge. The processing sequence in all these deformation processes can vary depending on the design, layout, and age of the steel plant.

3 DEVELOPMENT OF STEEL PROPERTIES

In order to produce a steel product with the desired properties, basic metallurgical principles are used to control three things:



This means that the steel composition and processing route must be closely controlled in order to produce the proper microstructure. The final microstructure is of utmost importance in determining the properties of the steel product. This section will explore how various microstructures are developed and the unique characteristics of each microstructural component in steel. The next section will discuss how alloy composition also plays a major role.

Iron–Carbon Equilibrium Diagram. Since most steels contain carbon, the basic principles of microstructural development can be explained by the iron–carbon equilibrium diagram. This diagram, shown in Fig. 1, is essentially a map of the phases that exist in iron at various carbon contents and temperatures under equilibrium conditions. Iron is an interesting chemical element in that it undergoes three phase changes when heated from room temperature to liquid. For example, from room temperature to 912°C pure iron exists as ferrite (also called alpha iron), from 912 to 1394°C it exists as austenite (gamma iron), from 1394 to 1538°C it exists as ferrite again (delta iron), and above 1538°C it is liquid. In other words, upon heating, iron undergoes allotropic-phase transformations from ferrite to austenite at 912°C, austenite to ferrite at 1394°C, and ferrite to liquid at 1538°C. Each transformation undergoes a change in crystal structure or arrangement of the iron atoms in the crystal lattice. It must be remembered that all chemical elements in their solid form have specific arrangements of atoms that are essentially the basic building blocks in producing the element in the form that we physically observe. These atomic arrangements form a latticework containing billions of atoms all aligned in a systematic way. Some of these lattices have a cubic arrangement, with an atom at each corner of the cube and another atom at the cube center. This arrangement is called body-centered-cubic (bcc). Others have an atom at each corner of the cube and atoms at the center of each face of the cube. This is called face-centered-cubic (fcc). Other arrangements are hexagonal, some are tetragonal, etc. As an example, pure iron as ferrite has a bcc arrangement. Austenite has a fcc arrangement. Upon heating, bcc ferrite will transform to fcc austenite at 912°C. These arrangements or crystal structures impart different properties to steel. For example, a bcc ferritic stainless steel will have properties much different from a fcc austenitic stainless steel, as described later in this chapter.

Since pure iron is very soft and of low strength, it is of little interest commercially. Therefore, carbon and other alloying elements are added to enhance properties. Adding carbon to pure iron has a profound effect on ferrite and austenite, discussed above. One way to understand the effect of carbon is to examine the iron–carbon diagram (Fig. 1). This is a binary (two-element) diagram of temperature and composition (carbon content) constructed under near-equilibrium conditions. In this diagram, as carbon is added to iron, the ferrite- and austenite-phase fields expand and contract depending upon the carbon level and temperature. Also, there are fields consisting of two phases, e.g., ferrite plus austenite.

Since carbon has a small atomic diameter when compared with iron, it is called an interstitial element because it can fill the interstices between the iron atoms in the cubic lattice. Nitrogen is another interstitial element. On the other hand, elements such as manganese, silicon, nickel, chromium, and molybdenum have atomic diameters similar to iron and are called substitutional alloying elements. These substitutional elements can thus replace iron atoms at the cube corners, faces, or center positions. There are many binary-phase diagrams (Fe–Mn, Fe–Cr, Fe–Mo, etc.) and tertiary-phase diagrams (Fe–C–Mn, Fe–C–Cr, etc.) showing the effect of interstitial and substitutional elements on the phase fields of ferrite and austenite. These diagrams are found in the handbooks listed at the end of the chapter.

Being an interstitial or a substitutional element is important in the development of steel properties. Interstitial elements such as carbon can move easily about the crystal lattice whereas a substitutional element such as manganese is much more difficult to move. The movement of

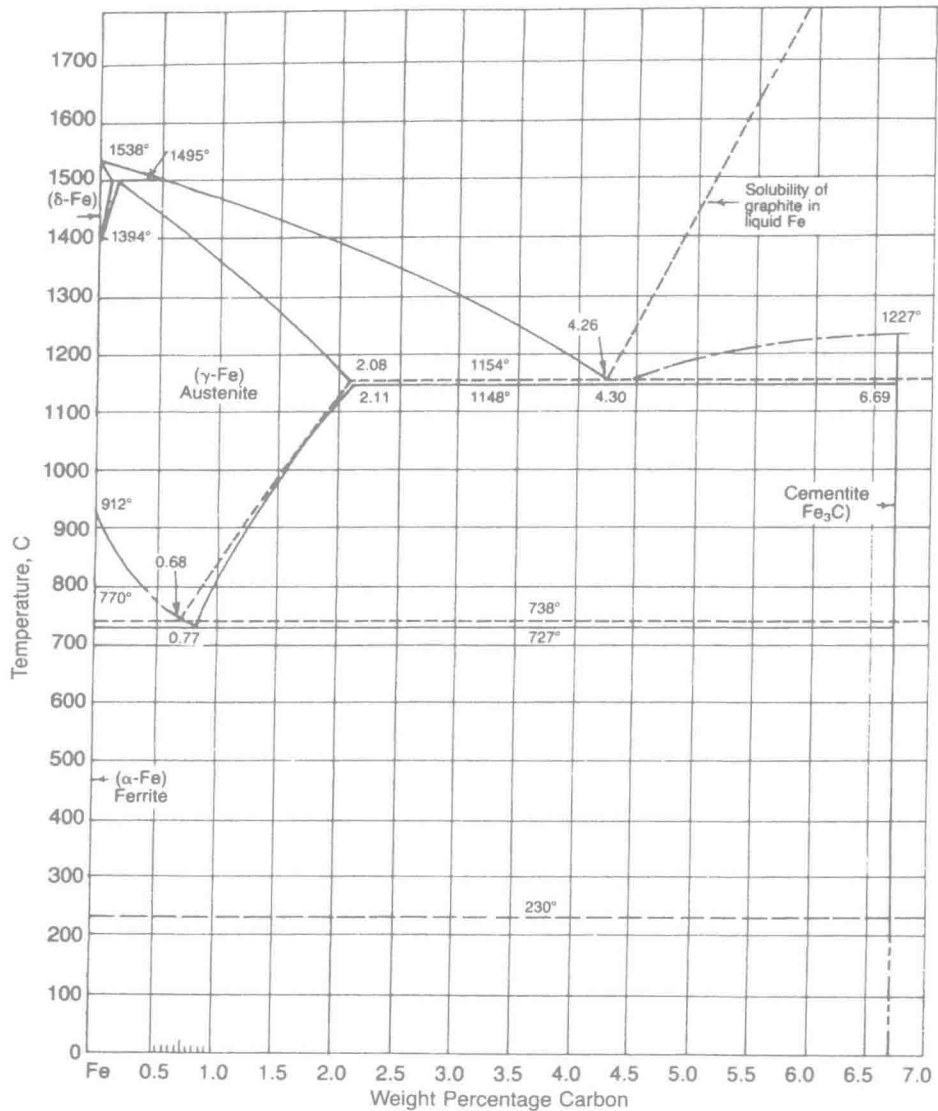


Figure 1 Iron-carbon binary-phase diagram. (Source: *Steels: Heat Treatment and Processing Principles*, ASM International, Materials Park, OH, 1990, p. 2.) Reprinted with permission of ASM International.

elements in a crystal lattice is called diffusion. Diffusion is a controlling factor in the development of microstructure. Another factor is solubility, which is a measure of how much of a particular element can be accommodated by the crystal lattice before it is rejected. In metals, when two or more elements are soluble in the crystal lattice, a solid solution is created (somewhat analogous to a liquid solution of sugar in hot coffee). For example, when added to iron, carbon has very limited solubility in ferrite but is about 100 times more soluble in austenite, as seen in the iron-carbon diagram in Fig. 2 (a limited version of the diagram in Fig. 1). The maximum solubility of carbon in ferrite is about 0.022% C at 727°C while the maximum