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TOOL AND MANUFACTURING ENGINEERS HANDBOOK

volume 3
Materials, Finishing and Coating

SME®

Editors: Charles Wick, CMfgE
Raymond F. Veilleux

FOURTH EDITION

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VOLUME III
MATERIALS, FINISHING AND COATING

A reference book for manufacturing engineers, managers, and technicians

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Revised under the supervision of
the SME Publications Committee
in cooperation with the SME
Technical Divisions

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PREFACE

The first edition, published as the *Tool Engineers Handbook* in 1949, established a useful and authoritative editorial format that was successfully expanded and improved upon in the publication of highly acclaimed subsequent editions, published in 1959 and 1976 respectively. Now, with continuing dramatic advances in manufacturing technology, increasing competitive pressure both in the United States and abroad, and a significant diversification of informational needs of the modern manufacturing engineer, comes the need for further expansion of the Handbook. As succinctly stated by Editor Frank W. Wilson in the preface to the second edition: "...no 'bible' of the industry can indefinitely survive the impact of new and changed technology."

Although greatly expanded and updated to reflect the latest in manufacturing technology, the nature of coverage in this edition is deeply rooted in the heritage of previous editions, constituting a unique compilation of practical data detailing the specification and use of modern manufacturing equipment and processes. Yet, the publication of this edition marks an important break with tradition in that this volume, dedicated to materials, finishing, and coating, is the third of five volumes to be published in the coming years, to comprise the fourth edition. Volume I, *Machining*, was published in March 1983, and Volume II, *Forming*, in April 1984. The final two volumes of this edition will be *Quality Control and Assembly* and *Management*.

The scope of this edition is multifaceted, offering a ready reference source of authoritative manufacturing information for daily use by engineers, managers, and technicians, yet providing significant coverage of the fundamentals of manufacturing processes, equipment, and tooling for study by the novice engineer or student. Uniquely, this blend of coverage has characterized the proven usefulness and reputation of SME Handbooks in previous editions and continues in this edition to provide the basis for acceptance across all segments of manufacturing.

The scope of this volume encompasses engineering materials, heat treatment, surface and edge preparation, and both inorganic and organic coatings. Materials discussed include the various steels, cast irons, nonferrous metals, plastics, advanced composites, and powdered metals. The heat treatment of steel and other metals, surface hardening, and heat treating furnaces are included.

A comprehensive section on surface and edge preparation includes individual chapters on mechanical and abrasive deburring and finishing; thermal, chemical, and electrochemical finishing; and cleaning. The section on inorganic coatings includes details on conversion coatings and anodizing, plating, electroless plating, thermal spraying and hard facing, porcelain enameling and hot dipping, vapor deposition, and special processes.

A separate section on organic coatings includes chapters on coating materials, application methods, curing methods, coating systems, and testing, troubleshooting, and safety. In-depth coverage of all subjects is presented in an easy-to-read format. A comprehensive index cross references

all subjects, facilitating the quick access of information. The liberal use of drawings, graphs, and tables also speeds information gathering and problem solving.

The reference material contained in this volume is the product of incalculable hours of unselfish contribution by hundreds of individuals and organizations, as listed at the beginning of each chapter. No written words of appreciation can sufficiently express the special thanks due these many forward-thinking professionals. Their work is deeply appreciated by the Society; but more important, their contributions will undoubtedly serve to advance the understanding of manufacturing technology throughout industry and will certainly help spur major productivity gains in the years ahead. Industry as a whole will be the beneficiary of their dedication.

Further recognition is due the members of the SME Publications Committee for their expert guidance and support as well as the many members of the SME Technical Activities Board—particularly the members of the Composites Council and the Burr, Edge and Surface Conditioning Technology (BEST) Division—and the Association for Finishing Processes of SME (AFP/SME).

The Editors

The Society of Manufacturing Engineers is a professional engineering society dedicated to advancing manufacturing technology through the continuing education of manufacturing managers, engineers, and technicians. The specific goal of the Society is "to advance scientific knowledge in the field of manufacturing engineering and to apply its resources to research, writing, publishing, and disseminating information."

The Society was founded in 1932 as the American Society of Tool Engineers (ASTE). From 1960 to 1969, it was known as the American Society of Tool and Manufacturing Engineers (ASTME), and in January 1970 it became the Society of Manufacturing Engineers. The changes in name reflect the evolution of the manufacturing engineering profession and the growth and increasing sophistication of a technical society that has gained an international reputation for being the most knowledgeable and progressive voice in the field.

As a member of the World Federation of Engineering Organizations, SME is the universally acknowledged technical society serving the manufacturing community. Among SME's activities are the following:

Associations of SME—The Society provides complete technical services and membership benefits through a number of associations. Each serves a special interest area. Members may join these associations in addition to SME. The associations are:

Association for Finishing Processes of SME (AFP/SME)

Computer and Automated Systems Association of SME (CASA/SME)

Machine Vision Association of SME (MVA/SME)

North American Manufacturing Research Institute of SME (NAMRI/SME)

Robotics International of SME (RI/SME)

Members and Chapters—The Society and its associations have some 80,000 members in 70 countries, most of whom are affiliated with SME's 380-plus senior chapters. The Society also has some 10,000 student members and more than 140 student chapters at colleges and universities in the United States and Canada.

Publications—The Society is involved in various publication activities encompassing handbooks, textbooks, videotapes, and magazines. Current periodicals include:

CIM Technology

Manufacturing Engineering

Manufacturing Insights (a video magazine)

Robotics Today

Technical Digest

Certification—This SME program formally recognizes manufacturing managers, engineers, and technologists based on experience and knowledge. The key certification requirement is successful completion of a two-part written examination covering (1) engineering fundamentals and (2) an area of manufacturing specialization.

Educational Programs—The Society annually sponsors over 200 conferences, expositions, and workshops throughout the world. It also operates the Center for Professional Development at its Dearborn, Michigan world headquarters.

CONTENTS

VOLUME III—MATERIALS, FINISHING AND COATING

ENGINEERING MATERIALS, CARBON AND ALLOY STEELS

ENGINEERING MATERIALS

Engineers today have at their disposal a multitude of materials that they can use to produce the products used in our rapidly developing society. These materials range from the ordinary materials that have been available for several hundred years to those that have recently been developed, and new materials are being introduced continuously.

This section of the Handbook, Volume III, contains nine individual chapters and is designed to provide the manufacturing engineer and other manufacturing professionals with the information they need to efficiently and effectively accomplish their respective roles. Information presented includes definitions of terms frequently encountered, brief discussions on how materials are produced, various material classifications, typical properties, current and potential applications, and descriptions of machinability, formability, and weldability.

A comprehensive discussion of machinability and machining of various materials can be found in Volume I, *Machining*, of this Handbook series; the forming of these materials is discussed in Volume II, *Forming*; and the assembly of these materials through various welding and joining processes can be found in Volume IV, *Quality Control and Assembly*. Heat treatment of ferrous and non-ferrous alloys are discussed in subsequent chapters of this volume.

Throughout this section, the mechanical properties and some chemical compositions of the most commonly used materials are presented in tabular form for comparison. Tabular data are not intended for use in specifications or design. For specific values and compositions, consult the material manufacturer.

The materials discussed in this section include carbon and alloy steels; stainless and maraging steels; cast steels and irons; nickel alloys and superalloys; titanium and molybdenum alloys; aluminum, copper, and magnesium alloys; lead, tin, and zinc alloys; plastics and composites; powdered metals; and some refractory metals. Not included in this discussion of materials are precious metals, pure metals, and glasses and ceramics. Cutting tool materials are discussed in Volume I, *Machining*, and tool and die materials are discussed in Volume II, *Forming*, of this Handbook series.

GLOSSARY OF TERMS

Terms commonly used with respect to engineering materials are presented in this section and are adapted from the glossary in the third edition of the *Tool and Manufacturing Engineers Handbook*, *Modern Steels and Their Properties*,[1] and *Heat Treater's Guide*.[2] Additional terms common to the heat treatment of metals appear in Chapter 10.

acid steel Steel melted in a furnace with an acid bottom and lining and under a slag containing an excess of an acid substance such as silica.

alloy A metal containing additions of other metallic or nonmetallic elements to enhance specific properties such as strength and corrosion resistance.

basic steel Steel melted in a furnace with a basic bottom and lining and under a slag containing an excess of a basic substance such as magnesia or lime.

Bayer process A process for extracting alumina from bauxite ore before the electrolytic reduction to aluminum metal.

blast furnace A shaft-type furnace using solid fuel (coke), air, and oxygen to smelt ore in a continuous operation.

Brinell hardness number (Bhn) A measure of hardness determined by the Brinell hardness test, which forces a hard steel or carbide ball of specific diameter into a material under a specified load.

brittleness The quality of a material that leads to fracture without appreciable plastic deformation.

capped steel A steel similar to rimmed steel in which the application of a mechanical or chemical cap renders the rimming action incomplete by causing the top metal to solidify.

carbon steel Steel that derives its properties from the presence of carbon without substantial amounts of other alloying elements.

cast iron A generic term for a large group of cast ferrous alloys containing over 2% carbon and 1% silicon.

cast steel Steel in the form of castings, characterized by a grain structure produced by solidification.

ENGINEERING MATERIALS

cold working Deforming metal plastically under conditions that induce strain hardening; usually performed at room temperature.

compacted graphite cast iron Cast iron having a graphite shape intermediate between the flake form of gray cast iron and the spherical form of ductile cast iron.

compressive strength The maximum compressive stress that a material can withstand without significant plastic deformation or fracture.

consumable electrode remelting A process for refining metals in which an electric current passes between an electrode made of the metal or alloy to be refined and an ingot of the refined metal under the protection of a vacuum, inert atmosphere, or slag covers.

continuous casting A casting technique that produces steel in the form of slabs, blooms, or billets directly from the ladle.

creep The flow or plastic deformation of metals held for long periods of time at stresses lower than the normal yield strength.

creep limit The maximum stress that will result in creep at a rate lower than an assigned rate.

damping capacity The ability of a metal to absorb vibrations, changing the mechanical energy into heat.

dead soft A temper of nonferrous alloys and some ferrous alloys corresponding to the condition of minimum hardness and tensile strength produced by full annealing.

density ratio The ratio of the apparent density of a powder metallurgy compact to the absolute density of metal of the same composition. Usually expressed as a percentage.

ductile cast iron Cast iron that has been treated with magnesium or cerium while molten to spheroidize the graphite and thereby impart ductility to the cast metal.

ductility The ability of a metal to undergo substantial amounts of plastic deformation before fracture.

elastic limit The maximum stress that a metal can withstand without exhibiting a permanent deformation upon release of the stress.

elongation The amount of permanent extension within a specified gage length, measured after fracture in the tension test; usually expressed as a percentage of the original gage length, such as 25% in 2″ (50 mm). Elongation may also refer to the amount of extension at any stage in any process that elongates a body continuously, as in rolling.

endurance limit The maximum stress that a metal can withstand without failure after a specified number of cycles of stress. If the term is employed without qualification, the cycles of stress are usually such as to produce complete reversal of flexural stress.

extra hard A temper of nonferrous and some ferrous alloys characterized by tensile strength and hardness about one third of the way from full-hard to extra-spring tempers.

extra spring A temper of nonferrous and some ferrous alloys corresponding approximately to a cold worked state above full hard beyond which further cold work will not measurably increase the strength and hardness.

fatigue The tendency of a metal to break under conditions of repeated cyclic stressing considerably below the tensile strength.

file hardness Hardness as determined by the use of a file of standardized hardness, on the assumption that a material cannot be cut with the file if the material is as hard as, or harder than, the file. Files covering a range of hardnesses may be employed.

flakes Short, discontinuous internal fissures in ferrous metals caused by localized internal stresses during cooling after hot working. Flaking may be associated with the presence of hydrogen in the steel.

free machining A term used to describe metals having alloying additions, such as lead, manganese, or sulfur, that reduce the tool force required in machining operations.

full hard A temper of nonferrous alloys and some ferrous alloys corresponding approximately to a cold worked state beyond which the material can no longer be formed by bending. In specifications, a full-hard temper is commonly defined in terms of minimum hardness or minimum tensile strength corresponding to a specific percentage of cold reduction following a full anneal.

grain An individual crystal in a metal or alloy.

grain size The average cross-sectional area or volume of grains in polycrystalline metals; usually expressed as average diameter or number of grains per unit of area or volume.

gray cast iron Cast iron that contains a large percentage of carbon in the form of flake graphite.

half hard A temper of nonferrous alloys and some ferrous alloys characterized by tensile strength about midway between that of dead-soft and full-hard tempers.

hardenability The relative ability of a ferrous alloy to form martensite when quenched from above the upper critical temperature.

hardness The resistance of a metal to indentation, defined in terms of the method of measurement.

heat treatment A sequence of controlled heating and cooling operations applied to a solid metal to impart desired properties.

inclusions Particles of nonmetallic compounds present in as-cast metals and carried over into wrought products. The shape and distribution of inclusions are changed by plastic deformation and contribute to directionality of mechanical properties.

ingot A casting intended for subsequent rolling, forging, or extrusion.

killed steel Steel treated with additions of silicon or aluminum to the melt to minimize the oxygen content so that no reaction occurs between carbon and oxygen during solidification.

machinability The relative ease with which materials can be shaped by cutting, drilling, or other chip-forming processes.

malleable cast iron A cast iron made by annealing white cast iron to eliminate some or all of the cementite.

mechanical properties The characteristics of a material that are displayed when a force is applied to the material. They

usually relate to the elastic or inelastic response of the material.

modulus of elasticity The ratio of stress to strain within the elastic range of a material; a measure of stiffness and the ability to resist deflection when loaded. Also referred to as Young's modulus.

modulus of rigidity The ratio of the shear stress to the shear strain in the elastic range. Also called the shear modulus.

notch impact strength A measure of the ability of a material to sustain high-velocity loading in the presence of a notch.

percent elongation See elongation.

percent reduction See reduction in area.

permanent set Plastic deformation.

physical properties Properties that pertain to the physics of a material, such as melting point, density, electrical and thermal conductivity, specific heat, and coefficient of thermal expansion.

plasticity The ability of a metal to undergo permanent deformation without rupture. (See also ductility.)

Poisson's ratio (μ) The ratio of the lateral expansion to the longitudinal contraction under a compressive load, or the ratio of the lateral contraction to the longitudinal expansion under a tensile load, provided the elastic limit is not exceeded.

powdered metals Metals and alloys in the form of fine particles, usually in the range of 39 μin. to 0.039" (1-1000 μm), or 1-1000 microns.

proportional limit The greatest stress that a material can sustain without any deviation from proportionality of stress to strain.

quarter hard A temper of nonferrous alloys and some ferrous alloys characterized by tensile strength about midway between that of dead-soft and half-hard tempers.

recrystallization The formation of new, strain-free grains by annealing a cold worked metal. Also called primary recrystallization.

reduction in area The difference between the original cross-sectional area and that of the smallest area at the point of rupture of a tensile test specimen. Usually stated as a percentage of the original area. A measurement of the material's ability to deform plastically in a localized manner.

residual stress Stresses present in a free metal body, usually as a result of prior, nonuniform plastic deformation, severe temperature gradients during quenching, or chemical differences as in carburized surfaces.

rimmed steel Low-carbon steel that does not contain significant percentages of easily oxidized elements such as aluminum, silicon, or titanium.

semikilled steel Steel that is incompletely deoxidized and contains sufficient dissolved oxygen to react with carbon to form carbon monoxide and offset solidification shrinkage.

shear Deformation in which parallel planes within the metal are displaced by sliding but retain their parallel relation to each other.

shear strength The maximum stress that a material can withstand before fracture when the load is applied parallel to the plane of stress.

strain, engineering The change in length divided by the original length, L/L_o. Expressed as a dimensionless number.

strain rate The rate at which deformation occurs.

stress, engineering Internal force reactions set up in a body when it is subjected to a load. Calculated by dividing the load by the original cross-sectional area.

temper The degree of ductility and toughness produced in a hardened metal by reheating to a temperature below the transformation range and then cooling at a suitable rate.

tensile strength The maximum engineering stress in tension that a material can withstand before rupture. Calculated by dividing the maximum load by the original cross-sectional area of a specimen pulled to failure in a tensile test.

three-quarters hard A temper of nonferrous alloys and some ferrous alloys characterized by tensile strength and hardness about midway between those of half-hard and full-hard tempers.

torsion modulus See modulus of rigidity.

torsional strength The maximum stress that a material can withstand before fracture when subjected to a torque or twisting force. Stress in torsion involves shearing stress, which is not uniformly distributed in a conventional torsion test bar.

toughness The ability of a material to absorb energy without failure when a load is applied rapidly, such as in an impact. Represented by the area under a stress-strain curve.

ultimate strength See tensile strength.

vacuum refining Melting and/or casting in vacuum to remove gaseous contaminants from a metal.

yield point The stress at which a pronounced increase in strain is shown without an increase in load; observed in low and medium-carbon steels.

yield strength The stress at which a material exhibits a specific amount of permanent deformation. In tensile tests, it is usually measured as the stress at 0.2% offset on a stress-strain diagram.

yield/tensile ratio The ratio of the yield point stress or yield strength to the tensile strength. Annealed low-carbon steels may have a ratio of only 40%, while heat-treated alloy steels and cold worked steels may have a ratio of 90% or higher. Low-carbon steels usually have a ratio of 50 to 70%.

MATERIAL PROPERTIES

Materials are usually selected for a particular application based on the properties that they possess and/or display under certain circumstances. The three main material property categories are chemical, physical, and mechanical.

Chemical Properties

It is not possible to make a sharp distinction between the chemical and physical properties of a metallic material. Both are dependent upon the crystal structure, the strength of interactive bonds, defects in the crystal lattice, and the amount

CHAPTER 1

ENGINEERING MATERIALS

and distribution of other phases within the body. Manufacturing engineers will be interested primarily in the interaction between metals and their environments. These include relative resistance to oxidation, galvanic corrosion caused by electrical contact between disimilar metals, general corrosion, and, especially, stress-corrosion cracking, which occurs in the simultaneous presence of a corroding agent and stress. The stress can be either residual or applied.

Physical Properties

The physical properties of a metal or alloy can be classified as thermal, electrical, magnetic, or optical. The thermal properties include melting temperature (or melting range), specific heat, thermal conductivity, and thermal expansion. The most important electrical properties are conductivity (and its inverse, resistivity) and superconductivity. Magnetic materials are either soft or hard. In the former, the direction of magnetization can be altered with little expenditure of energy. In the latter, the magnetization is permanent, which means that a large expenditure of energy is required to alter the direction. Soft magnetic materials are required for generators, motors, and transformers. Hard magnetic materials are used wherever permanent magnets are needed. The optical properties of a solid depend upon the type of interatomic bonding. Metallic bonding is responsible for the color, reflectivity, and emissivity of metallic surfaces.

Mechanical Properties

Mechanical properties are the characteristics of a material that are displayed when a force is applied. The mechanical properties of a material are usually the primary factors in selecting a material for a specific application.
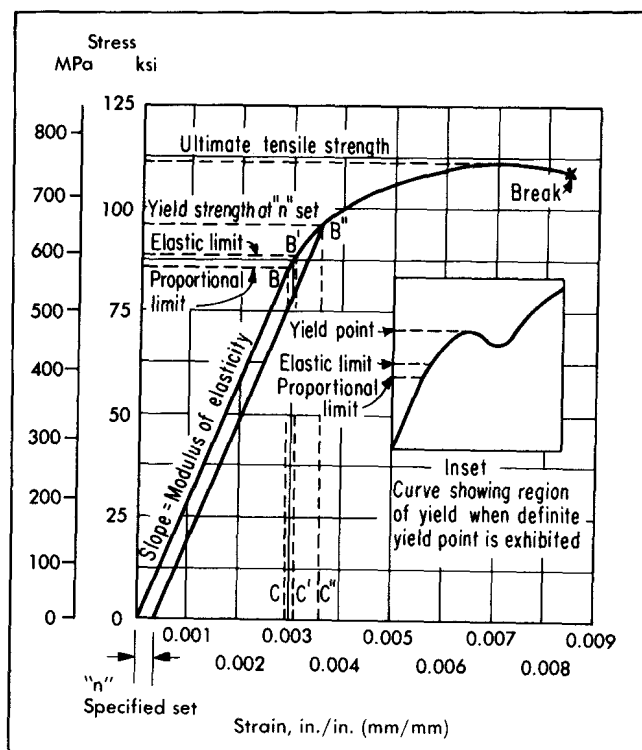
Fig. 1-1 A stress-strain diagram is a plot of the stress required to produce a given strain during a tensile test. The tensile strength, yield strength, and modulus of elasticity of a given material can be obtained from this diagram.

TABLE 1-1
Comparison of Density and Modulus of Elasticity of Commonly Used Engineering Materials

Material	Density, lb/in.^{3} (g/cm^3)	Modulus of Elasticity, psi x 10^6 (GPa)
Wrought steels	0.280-0.290 (7.76-8.03)	28.0-31.0 (193-215)
Cast steels		
Carbon and low alloy	0.282-0.285 (7.81-7.90)	29.3-31.4 (202-217)
High alloy*	0.272-0.294 (7.53-8.14)	24.0-29.0 (165-200)
Cast irons	0.251-0.280 (6.95-7.76)	9.6-28.0 (66-193)
Nickel alloys	0.282-0.334 (7.81-9.25)	24.0-30.0 (165-207)
Molybdenum alloys	0.369 (10.22)	46 (317)
Titanium alloys	0.158-0.175 (4.38-4.85)	15.0-17.9 (103-123)
Superalloys		
Iron based	0.286-0.291 (7.92-8.06)	
Nickel based	0.280-0.319 (7.76-8.84)	28.6-31.6 (197-218)
Cobalt based	0.290-0.333 (8.03-9.23)	29.5-32.6 (203-225)
Aluminum alloys	0.097-0.102 (2.69-2.83)	10.0-11.4 (69-79)
Magnesium alloys	0.064-0.067 (1.77-1.86)	6.5 (45)
Copper alloys	0.301-0.323 (8.34-8.95)	14.0-22.0 (97-152)
Lead alloys	0.351-0.410 (9.72-11.36)	2.0 (14)
Tin alloys	0.262-0.304 (7.25-8.42)	6.03 (41.6)
Zinc alloys	0.188-0.259 (5.21-7.18)	6.2-14.0 (43-97)
Powdered metals		
Ferrous	0.209-0.267 (5.80-7.40)	10.5-23 (72-159)
Nonferrous	0.047-0.296 (1.30-8.20)	
Plastics		
Thermosetting	0.0397-0.0632 (1.1-1.75)	1.0-1.5 (6.9-10.3)
Thermoplastic	0.0328-0.0769 (0.91-2.13)	0.025-4.0 (0.17-28)

Note: Values are based on materials at room temperature.
* The modulus of elasticity is sensitive to the material's crystalline structure and grain orientation. The range given is for equiaxed structures; columnar structures are lower.

Mechanical properties provide the engineer with information regarding strength, formability, rigidity, toughness, and durability. In the subsequent chapters, the tensile strength, yield strength, total elongation, and hardness are given in tabular form for commonly used materials. Figure 1-1 shows the tensile strength, yield strength, yield point, and modulus of elasticity of a material on a typical stress-strain diagram. The modulus of elasticity range and density are given in Table 1-1 to permit comparison of these values for various materials. Table 1-2 shows the approximate relations between various hardness scales for steel having uniform chemical composition and heat treatment.[3] The approximate tensile strengths for corresponding hardnesses are also given. These relations usually apply to only steels with uniform chemical composition and heat treatment.

The mechanical, physical, and chemical properties of a metal are sensitively dependent upon crystal structure. Engineering materials almost invariably have one of three structures: body-centered cubic (bcc), face-centered cubic (fcc), or hexagonal close-packed (hcp).

The mechanical properties of bcc metals are dependent upon temperature and the strain rate. As temperature is reduced and the strain rate increased, the strength of the metal increases rapidly and the ductility and toughness decrease. In contrast, strain rate and temperature changes have little effect on the mechanical properties of fcc metals. Often they are more easily formed than bcc metals. Hexagonal close-packed metals are generally more difficult to form than either bcc or fcc metals owing to the small number of slip systems that can operate in the hcp structures.

CARBON STEELS

Iron and carbon are the predominant elements in steels. Carbon content ranges from a few hundredths to about one percent. The amount of additional alloying elements determines whether the steel is considered to be a carbon or an alloy steel.

Steel is considered a carbon steel when no minimum content is specified or required for aluminum (except for oxidation or to control grain size), chromium, cobalt, columbium, molybdenum, nickel, titanium, tungsten, vanadium, zirconium, or any other element to obtain a desired alloying effect; when the specified minimum for copper does not exceed 0.40%; or when the addition of manganese, silicon, and copper is limited to a maximum of 1.65%, 0.60%, and 0.60% respectively.

On the basis of carbon content, carbon steels can be divided into three groups. The first group contains 0.001-0.30% carbon and is considered low-carbon steel. The second group contains 0.30-0.70% carbon and is considered medium-carbon steel. The third group contains 0.70-1.30% carbon and is considered high-carbon steel.

Certain grades may also specify the addition of boron to improve hardenability and aluminum for deoxidation and to control grain size. Carbon steels also contain small quantities of residual elements or impurities from the raw material such as copper, nickel, molybdenum, chromium, phosphorus, and sulfur, which are considered incidental.

Carbon steels may be classified according to chemical composition, deoxidation practice, quality, and end-product forms. Common end-product forms include bar, sheet/strip, plate, wire, tubing, and structural shapes. Carbon steel may also be classified as hot rolled or cold drawn (cold rolled when referring to sheets). Cold finished steels are produced from hot rolled steel by several cold finishing processes, resulting in improved surface finishes, dimensional accuracy, alignment, or machinability; elongation and yield and tensile strengths are increased. Cold rolled sheets are available in different tempers and can be precoated with zinc, aluminum, terne (lead-tin alloy), tin, and organic coatings.

STEELMAKING PRACTICE

Steelmaking may be described as the process of refining pig iron or ferrous scrap by removing undesirable elements from the melt and then adding desired elements in predetermined amounts. The additions are often the same elements that were originally removed, the difference being that the elements present in the final steel product are in the proper proportion to produce the desired properties.[4]

The various practices employed in steel production have a direct influence on the type and quality of the finished product. To ensure a quality finished product, it is necessary to exercise control over the raw materials used and to employ the proper melting, refining, and casting techniques.

Melting and Refining Techniques

The melting of pig iron in the production of steel is performed in basic oxygen, electric, and open-hearth furnaces. Before the molten metal is poured, it is sometimes subjected to a vacuum treatment that lowers the content of hydrogen and oxygen gases, minimizes slow cooling time, and improves alloy distribution and mechanical properties. The two types of vacuum treatments used are vacuum degassing and vacuum carbon deoxidation (VCD).

In recent years, ladle metallurgy has been adopted for refining steel. Ladle metallurgy permits the steelmaking processes to operate in a lower cost and higher productivity mode, while simultaneously ensuring production of high-quality steels.[5] The various treatments in ladle metallurgy are synthetic slag treatments, gas stirring or purging, direct immersion of reactants, lance injection of reactants, and wire feeding of reactants for the purpose of removing undesired elements such as oxygen, hydrogen, sulfur, and phosphorus. The treatments may be performed separately or in combination to achieve the desired results.

Casting Techniques

In wrought steel production, the molten steel is poured into tapered molds or into a strand-casting machine. Techniques for producing steel castings are discussed in Volume II, *Forming*, of this Handbook series.

Ingot casting. In ingot casting, the molten metal is poured into tapered, cast iron molds and allowed to solidify. The solidified metal is referred to as an ingot. Ingots can be square, rectangular, or round in cross section, with round corners and corrugated sides. The size of the ingot ranges from a few hundred pounds to several hundred tons.

CARBON STEELS

TABLE 1-2
Comparison of Commonly Used Hardness Scales for Steel[3]

Brinell Indenta-tion Diam, mm	Brinell Hardness No., 10 mm Ball, 3000 kg Load			Diamond Pyramid Hardness No.	Rockwell Hardness No. **				Rockwell Superficial Hardness No., Super-ficial Brale Penetrator			Shore Sclero-scope Hardness No.	Tensile Strength (approxi-mate), ksi (MPa)
	Standard Ball	Hultgren Ball	Tungsten-Carbide Ball		A-Scale, 60 kg Load, Brale Penetrator	B-Scale, 100 kg Load, 1/16 in. Diam Ball	C-Scale, 150 kg Load, Brale Penetrator	D-Scale, 100 kg Load, Brale Penetrator	15-N Scale, 15 kg Load	30-N Scale, 30 kg Load	45-N Scale, 45 kg Load		
	—	—	—	940	85.6	—	68.0	76.9	93.2	84.4	75.4	97	—
	—	—	—	920	85.3	—	67.5	76.5	93.0	84.0	74.8	96	—
	—	—	—	900	85.0	—	67.0	76.1	92.9	83.6	74.2	95	—
	—	—	767	880	84.7	—	66.4	75.7	92.7	83.1	73.6	93	—
	—	—	757	860	84.4	—	65.9	75.3	92.5	82.7	73.1	92	—
2.25	—	—	745	840	84.1	—	65.3	74.8	92.3	82.2	72.2	91	—
	—	—	733	820	83.8	—	64.7	74.3	92.1	81.7	71.8	90	—
	—	—	722	800	83.4	—	64.0	73.8	91.8	81.1	71.0	88	—
2.30	—	—	712	—	—	—	—	—	—	—	—	—	—
	—	—	710	780	83.0	—	63.3	73.3	91.5	80.4	70.2	87	—
	—	—	698	760	82.6	—	62.5	72.6	91.2	79.7	69.4	86	—
2.35	—	—	684	740	82.2	—	61.8	72.1	91.0	79.1	68.6	—	—
	—	—	682	737	82.2	—	61.7	72.0	91.0	79.0	68.5	84	—
	—	—	670	720	81.8	—	61.0	71.5	90.7	78.4	67.7	83	—
	—	—	656	700	81.3	—	60.1	70.8	90.3	77.6	66.7	—	—
2.40	—	—	653	697	81.2	—	60.0	70.7	90.2	77.5	66.5	81	—
	—	—	647	690	81.1	—	59.7	70.5	90.1	77.2	66.2	—	—
	—	—	638	680	80.8	—	59.2	70.1	89.8	76.8	65.7	80	—
	—	—	630	670	80.6	—	58.8	69.8	89.7	76.4	65.3	—	—
2.45	—	—	627	667	80.5	—	58.7	69.7	89.6	76.3	65.1	79	—
2.50	—	601	—	677	80.7	—	59.1	70.0	89.8	76.8	65.7	—	—
	—	—	601	640	79.8	—	57.3	68.7	89.0	75.1	63.5	77	—
2.55	—	578	—	640	79.8	—	57.3	68.7	89.0	75.1	63.5	—	—
	—	—	578	615	79.1	—	56.0	67.7	88.4	73.9	62.1	75	—
2.60	—	555	—	607	78.8	—	55.6	67.4	88.1	73.5	61.6	—	—
	—	—	555	591	78.4	—	54.7	66.7	87.8	72.7	60.6	73	298 (2053)
2.65	—	534	—	579	78.0	—	54.0	66.1	87.5	72.0	59.8	—	292 (2013)
	—	—	534	569	77.8	—	53.5	65.8	87.2	71.6	59.2	71	288 (1986)
2.70	—	514	—	553	77.1	—	52.5	65.0	86.7	70.7	58.0	—	278 (1917)
	—	—	514	547	76.9	—	52.1	64.7	86.5	70.3	57.6	70	274 (1889)
2.75	495	—	—	539	76.7	—	51.6	64.3	86.3	69.9	56.9	—	269 (1855)
	—	495	—	530	76.4	—	51.1	63.9	86.0	69.5	56.2	—	265 (1827)
	—	—	495	528	76.3	—	51.0	63.8	85.9	69.4	56.1	68	264 (1820)

TABLE 1-2—Continued

Brinell Indentation Diam, mm	Brinell Hardness No., 3000 kg Load			Diamond Pyramid Hardness No.	Rockwell Hardness No. **				Rockwell Superficial Hardness No., Superficial Brale Penetrator			Shore Scleroscope Hardness No.	Tensile Strength (approximate), ksi (MPa)
	Standard Ball	Hultgren Ball	Tungsten-Carbide Ball		A-Scale, 60 kg Load, Brale Penetrator	B-Scale, 100 kg Load, 1/16 in. Diam Ball	C-Scale, 150 kg Load, Brale Penetrator	D-Scale, 100 kg Load, Brale Penetrator	15-N Scale, 15 kg Load	30-N Scale, 30 kg Load	45-N Scale, 45 kg Load		
2.80	477	–	–	516	75.9	–	50.3	63.2	85.6	68.7	55.2	–	258 (1779)
	–	477	–	508	75.6	–	49.6	62.7	85.3	68.2	54.5	–	252 (1738)
	–	–	477	508	75.6	–	49.6	62.7	85.3	68.2	54.5	66	252 (1738)
2.85	461	–	–	495	75.1	–	48.8	61.9	84.9	67.4	53.5	–	244 (1682)
	–	461	–	491	74.9	–	48.5	61.7	84.7	67.2	53.2	–	242 (1667)
	–	–	461	491	74.9	–	48.5	61.7	84.7	67.2	53.2	65	242 (1667)
2.90	444	–	–	474	74.3	–	47.2	61.0	84.1	66.0	51.7	–	231 (1593)
	–	444	–	472	74.2	–	47.1	60.8	84.0	65.8	51.5	–	230 (1586)
	–	–	444	472	74.2	–	47.1	60.8	84.0	65.8	51.5	63	230 (1586)
2.95	429	429	429	455	73.4	–	45.7	59.7	83.4	64.6	49.9	61	219 (1510)
3.00	415	415	415	440	72.8	–	44.5	58.8	82.8	63.5	48.4	59	212 (1462)
3.05	401	401	401	425	72.0	–	43.1	57.8	82.0	62.3	46.9	58	202 (1393)
3.10	388	388	388	410	71.4	–	41.8	56.8	81.4	61.1	45.3	56	193 (1331)
3.15	375	375	375	396	70.6	–	40.4	55.7	80.6	59.9	43.6	54	184 (1269)
3.20	363	363	363	383	70.0	–	39.1	54.6	80.0	58.7	42.0	52	177 (1220)
3.25	352	352	352	372	69.3	(110.0)	37.9	53.8	79.3	57.6	40.5	51	171 (1179)
3.30	341	341	341	360	68.7	(109.0)	36.6	52.8	78.6	56.4	39.1	50	164 (1131)
3.35	331	331	331	350	68.1	(108.5)	35.5	51.9	78.0	55.4	37.8	48	159 (1096)
3.40	321	321	321	339	67.5	(108.0)	34.3	51.0	77.3	54.3	36.4	47	154 (1062)
3.45	311	311	311	328	66.9	(107.5)	33.1	50.0	76.7	53.3	34.4	46	149 (1027)
3.50	302	302	302	319	66.3	(107.0)	32.1	49.3	76.1	52.2	33.8	45	146 (1007)
3.55	293	293	293	309	65.7	(106.0)	30.9	48.3	75.5	51.2	32.4	43	141 (972)
3.60	285	285	285	301	65.3	(105.5)	29.9	47.6	75.0	50.3	31.2	–	138 (952)
3.65	277	277	277	292	64.6	(104.5)	28.8	46.7	74.4	49.3	29.9	41	134 (924)
3.70	269	269	269	284	64.1	(104.0)	27.6	45.9	73.7	48.3	28.5	40	130 (896)
3.75	262	262	262	276	63.6	(103.0)	26.6	45.0	73.1	47.3	27.3	39	127 (876)
3.80	255	255	255	269	63.0	(102.0)	25.4	44.2	72.5	46.2	26.0	38	123 (848)
3.85	248	248	248	261	62.5	(101.0)	24.2	43.2	71.7	45.1	24.5	37	120 (827)
3.90	241	241	241	253	61.8	100.0	22.8	42.0	70.9	43.9	22.8	36	116 (800)
3.95	235	235	235	247	61.4	99.0	21.7	41.4	70.3	42.9	21.5	35	114 (786)
4.00	229	229	229	241	60.8	98.2	20.5	40.5	69.7	41.9	20.1	34	111 (765)
4.05	223	223	223	234	–	97.3	(18.8)	–	–	–	–	–	–

TABLE 1-2—Continued

Brinell Indentation Diam, mm	Brinell Hardness No.,* 10 mm Ball, 3000 kg Load			Diamond Pyramid Hardness No.	Rockwell Hardness No.**				Rockwell Superficial Hardness No., Superficial Brale Penetrator			Shore Scleroscope Hardness No.	Tensile Strength (approximate), ksi (MPa)
	Standard Ball	Hultgren Ball	Tungsten-Carbide Ball		A-Scale, 60 kg Load, Brale Penetrator	B-Scale, 100 kg Load, 1/16 in. Diam Ball	C-Scale, 150 kg Load, Brale Penetrator	D-Scale, 100 kg Load, Brale Penetrator	15-N Scale, 15 kg Load	30-N Scale, 30 kg Load	45-N Scale, 45 kg Load		
4.10	217	217	217	238	—	96.4	(17.5)	—	—	—	—	33	105 (724)
4.15	212	212	212	222	—	95.5	(16.0)	—	—	—	—	—	102 (703)
4.20	207	207	207	218	—	94.6	(15.2)	—	—	—	—	32	100 (690)
4.25	201	201	201	212	—	93.8	(13.8)	—	—	—	—	31	98 (676)
4.30	197	197	197	207	—	92.8	(12.7)	—	—	—	—	30	95 (655)
4.35	192	192	192	202	—	91.9	(11.5)	—	—	—	—	29	93 (641)
4.40	187	187	187	196	—	90.7	(10.0)	—	—	—	—	—	90 (620)
4.45	183	183	183	192	—	90.0	(9.0)	—	—	—	—	28	89 (614)
4.50	179	179	179	188	—	89.0	(8.0)	—	—	—	—	27	87 (600)
4.55	174	174	174	182	—	87.8	(6.4)	—	—	—	—	—	85 (586)
4.60	170	170	170	178	—	86.8	(5.4)	—	—	—	—	26	83 (572)
4.65	167	167	167	175	—	86.0	(4.4)	—	—	—	—	—	81 (558)
4.70	163	163	163	171	—	85.0	(3.3)	—	—	—	—	25	79 (545)
4.80	156	156	156	163	—	82.9	(0.9)	—	—	—	—	—	76 (524)
4.90	149	149	149	156	—	80.8	—	—	—	—	—	23	73 (503)
5.00	143	143	143	150	—	78.7	—	—	—	—	—	22	71 (490)
5.10	137	137	137	143	—	76.4	—	—	—	—	—	21	67 (462)
5.20	131	131	131	137	—	74.0	—	—	—	—	—	—	65 (448)
5.30	126	126	126	132	—	72.0	—	—	—	—	—	20	63 (434)
5.40	121	121	121	127	—	69.8	—	—	—	—	—	19	60 (414)
5.50	116	116	116	122	—	67.6	—	—	—	—	—	18	58 (400)
5.60	111	111	111	117	—	65.7	—	—	—	—	—	15	56 (386)

(Society of Automotive Engineers)

Note: Some of the values shown in this table correspond to values in the corresponding joint SAE-ASM-ASTM Committee on Hardness Conversions as printed in ASTM E 140.

* Brinell numbers are based on the diameter of impressed indentation. If the ball distorts (flattens) during test, Brinell numbers will vary in accordance with the degree of such distortions when related to hardnesses determined with Vickers Diamond Pyramid, Rockwell Brale, or other penetrator which does not sensibly distort. At high hardnesses, therefore, the relationship between Brinell, Vickers, or Rockwell scales is affected by the type of ball used. Steel balls (Standard or Hultgren) tend to flatten slightly more than carbide balls, resulting in larger indentation and lower Brinell number than shown by a carbon ball.

** Values in ( ) are beyond normal range and are given for information only.

After the ingots are stripped from the molds, they are held in a furnace or soaking pit to equalize the temperature throughout. When the suitable temperature has been attained, the ingot is rolled or forged into blooms, billets, or slabs through a series of mill operations.

Strand (continuous) casting. Strand casting is the direct casting of steel from the ladle into slabs, blooms, or billets. The process can be performed vertically or horizontally. In operation, the molten steel is poured from the ladle into an intermediate vessel, called a tundish, at the top of the strand-casting machine. The tundish acts as a reservoir for the molten steel and regulates the rate at which the molten steel flows into one or more oscillating, water-cooled molds. The water-cooled, open-ended molds incorporate the desired cross section of the slab, bloom, or billet.

Solidification of the steel begins in the mold and is completed by cooling the moving steel surface. The steel produced from one or more ladle through one mold is commonly referred to as a strand. Several strands may be cast simultaneously, depending on the size of the ladle and the cross section of the strand. A reduction in strand size may be carried out by hot working before cutting the strand into proper lengths. When two or more ladles are cast without interruption, the process is called continuous casting.

Strand or continuous casting techniques are being increasingly employed in the steel industry. Several advantages of the process include more uniform chemical composition and mechanical properties in the semifinished product, and increased productivity over ingot casting. Continuous casting methods are also being used in the production of copper and aluminum alloys, and gray and alloy-type cast irons.

TYPES OF STEEL

The principal reaction in steelmaking is the removal of excess carbon by the combination of carbon and oxygen to form a gas. If the extra oxygen remaining after this reaction is not removed prior to or during casting, the gaseous products continue to evolve during solidification. The type of steel produced is determined by the amount of deoxidation that takes place before casting. The four types of carbon steels produced are killed, semikilled, rimmed, and capped.

Killed Steels

Killed steels are strongly deoxidized by the addition of aluminum and/or silicon to the ladle before pouring. These elements combine with the oxygen; thus, only a negligible evolution of gases occurs during solidification. Killed steels are characterized by a high degree of uniformity in chemical composition and mechanical properties, which render them suitable for applications requiring forging, extrusion, severe cold forming, carburizing, and heat treatment. However, there may be variations in composition depending on the steelmaking practice used.

Semikilled Steels

Semikilled steels have characteristics intermediate between those of killed and rimmed steels. During solidification, the evolved gas is entrapped within the body of the ingot and counteracts the shrinkage.

Rimmed Steels

Rimmed steels are generally low-carbon steels that do not contain significant percentages of easily oxidized elements such as aluminum, silicon, or titanium. Since deoxidation is minimal, the carbon and residual oxygen react during solidification. The reaction stirs the liquid metal causing the metal that solidifies at the outer rim of the ingot to be lower in carbon, phosphorus, and sulfur than the average composition, whereas the inner portion, or core, is higher than average in those elements. The rimming action may continue until the reactions stop and the top of the ingot solidifies, or it may be stopped mechanically or chemically.

Rimmed steels have good surface and ductility characteristics. Because of their ductility, rimmed steels are suitable for moderate cold forming applications.

Capped Steels

Capped steels have characteristics similar to those of rimmed steel. The rimming action is controlled when the steel is cast so that gas produced during solidification causes the metal to rise in the mold. Capping occurs when the rising metal contacts a heavy metal cap placed on the bottle-top mold (mechanical capping). Adding ferrosilicon or aluminum to the ingot top after the ingot has rimmed for the desired period of time is another method of producing capped steel (chemical capping).

GRADES OF STEEL

Grade usually denotes the chemical composition of a particular steel. The grades may vary in chemical composition from almost pure iron to a material of complex constitution. A particular grade of carbon steel usually has specified limits for various elements, but the properties of products made from that grade can be diverse.

Lists of standard steels designed to serve the needs of fabricators and users of steel products are published by the American Iron and Steel Institute (AISI) and the Society of Automotive Engineers (SAE). The general acceptance and use of standard steels since their inception in 1941 have demonstrated that these steels have, in most cases, successfully replaced the many steels of specialized compositions previously used. The list is altered from time to time to accommodate steels of proven merit and to provide for changes that develop in industry. There are still specialized steels being produced, however, for particular applications.

Grade Designation

A four-numeral series, adopted by the AISI and the SAE, is used to designate standard carbon steels specified to chemical composition ranges. It is important to note that these designations do not indicate specifications. The prefix M is used to designate a series of merchant-quality steels and the suffix H designates standard hardenability steels.

The first two digits indicate the steel type and identifying elements as shown in Table 1-3. The last two digits indicate the approximate mean of the carbon range. For example, in the grade designation 1035, 35 represents a carbon range of 0.32 to 0.38%. It is necessary to deviate from this system and to interpolate numbers in the case of some carbon ranges and for variations in manganese, phosphorus, or sulfur with the same range. Special-purpose elements such as lead and boron are designated by inserting the letter L or B, respectively, between the second and third numerals.

In 1975, the Unified Numbering System (UNS) for Metals and Alloys was established by the American Society for Testing and Materials (ASTM) and the SAE. The UNS number consists of a single letter prefix followed by five digits. The letter G indicates standard carbon steels, and H indicates standard