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MACHINE DESIGN DATABOOK

SECOND EDITION

K. LINGAIAH

MACHINE DESIGN DATABOOK

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Second Edition

McGraw-Hill

New York Chicago San Francisco Lisbon London Madrid
Mexico City Milan New Delhi San Juan Seoul
Singapore Sydney Toronto

ISBN: 978-0-07-150049-4

MHID: 0-07-150049-9

The material in this eBook also appears in the print version of this title: ISBN: 978-0-07-136707-3, MHID: 0-07-136707-1.

CONTENTS

PREFACE

"Machine design" is an interdisciplinary subject in mechanical engineering. It draws information from thermal science, mechanics of solids, theory of elasticity, fluid science, material science, engineering mechanics, experimental stress analysis, production engineering, and some other branches of sciences. Machine design, therefore, assimilates more information from these disciplines than does any other engineering subject.

It is indeed gratifying that the first edition of *Machine Design Databook* published by McGraw-Hill in the year 1994 was so well received by the students, teachers, designers, practicing engineers, and working professionals that within a short period after its publication all the copies were sold out. The encouraging reception accorded to the first edition of this Databook has inspired the author to enhance its usefulness further by enlarging it. One of the several reasons for publishing a new second edition of any engineering handbook is to update the technical material and to take advantage of the enhanced receptivity of the readers. The present edition has been enlarged by including several tables, new drawings, and equations and by adding three new chapters–namely–"Elements of Machine Tool Design," "Applied Elasticity," and "Retaining Rings and Circlips". The author hopes that the inclusion of these will be of immense help to students, teachers, designers, practicing engineers, and working professionals in machine design.

The writer of any handbook on an engineering subject has to keep in touch with the developments taking place on the borders of discovery and frontiers of research in the subject, i.e., in all related subjects. This requires extensive study of the burgeoning literature on the subject both in the form of books and in the form of technical papers in professional journals. The author has left no stone unturned in reading all of the latest literature available on the subject to update the Databook and also to enhance its professional value. The present revised edition, therefore, makes a distinct improvement over its predecessor in contents, presentation, and arrangement by adding three new chapters.

Machine Design Databook provides weights and measures both in SI and fps, i.e., U.S. Customary System units, for the benefit of students, teachers, designers, practicing engineers, and working professionals.

The properties of engineering materials, presented in this Databook in Chapter 1, are taken from ANSI, ISO, ASME, Det Norske Veritas Classification, DIN, UNS (SAE), AISI, ASTM, and Indian Standards and are in both SI and U.S. Customary System units. All formulas (empirical, semi-empirical and otherwise), charts, graphs and tables are in both SI and US Customary units.

All elementary deflection, stress, strain, moments and torsion equations under static and dynamic conditions are given in Chapters 2 and 3. Chapter 4, on stress concentration and stress intensity in machine members, includes formulas, graphs, and tables for theoretical and fatigue stress concentration factors and stress intensity factors for bolts, nuts, screws, weldments, plates with and without cutouts (holes) of various shapes, shoulders, and notches in shafts and plates etc. Chapter 5 treats the design of machine elements for strength. The factor of safety, size effect, surface finish, reliability, corrosion, temperature effect, fatigue and stochastic approach are considered in this chapter. A number of design equations and data are given in Chapter 6 for design of cams.

The design of boilers, pressure vessels, boiler tubes and pipes, shells and plates with latest data from ASME Boilers and Pressure Vessels Code and Indian Standards for Unfired Pressure Vessels are presented in Chapters 7, 8, and 9. The design equations, charts, graphs, and tables are presented in a more accessible and useful form for the designers, students, teachers, and practicing engineers. The equations and data in Chapters 10 and 15 provide sufficient information for the design of rotating disks and cylinders and flywheels. Most of the material included in Chapter 11 on metal fits, tolerances, and surface texture uses SI units. Sufficient information is also given in U.S. Customary System units for the benefit of students, designers, and practicing engineers in this chapter.

Chapters 12 and 13, which include stress formulas and exhaustive information on design of welded joints and riveted joints, are written so that students, designers, teachers, and practicing engineers can quickly find the information they search for. Updated information for the design and selection of seals and packings is provided in Chapter 16. Design of shafts is exhaustively dealt with in Chapter 14, as are all theories of failures. This chapter includes the equations with sufficient data to solve shaft problems.

In Chapter 17, design equations for knuckle joint, cotter joint, pins, keys and splines are given in addition to data from standards. Chapter 18, on threaded fasteners and screws for power transmission, covers ISO standards for bolts and nuts in addition to other fps standards. Standard formulas and data for threaded connections, preloaded and tension-loaded bolts joints, and power screws were thoroughly scanned, and updated information is given in this chapter. In Chapter 19 there is extensive inclusion of formulas, standard graphs, and data for the design of couplings, clutches, and brakes. The data and design equations in this chapter are sufficient to design components of couplings, clutches, and brakes. The chapter also includes the latest information on brake- and clutch-facing materials.

Chapter 20, on springs, includes tolerances on helical spring wire diameter, and coil diameter, and free-length and cross-section load, length, and width tolerances of leaf spring for motor vehicle suspension. The spring constant and other design aspects of springs can be studied from this chapter. New materials have been brought into this chapter and rational design of springs can be carried out by using size factor, surface finish factor, statistical data, and other information.

The long felt need for a rational selection of standard materials for flexible machine elements has been, to a large extent, overcome by the presentation of the required number of standard charts, tables, and equations in Chapter 21. Rating formulas for chains and belts have been given in this chapter for the benefit of students, teachers, designers, and practicing engineers.

Chapter 22, on mechanical vibration, is included in this Databook to cover the design of machines so that they work safely within the allowable vibration limits without breakdown during operation.

The topic of sliding contact bearings in Chapter 23 has been thoroughly updated including a large number of charts and tables. The inclusion of this data on the composition and properties of bearing materials and lubricants and guides for the selection of design factors are very useful for students, teachers, designers, and practicing engineers. The dimensions and load rating under static and dynamic conditions of rolling contact bearings such as deep-groove, self-aligning, angular-contact and thrust, ball and roller bearings from different manufacturers catalogues like FAG, SKF, and Indian standards have been listed and compared. Importance is given to the estimation of the equivalent loads in bearings under different operating conditions. The subjects of tribology along with design of bearings were added to help the students, teachers, and practicing engineers to understand and design bearings more effectively. Friction, wear, and lubrication, which constitute the study of tribology, are seldom given any importance in any of the data handbooks of machine design except in *Tribology Handbook* by M. J. Neale and in this Databook. These topics help in the study of the distress condition of bearings and gears to prevent failures of these machine elements in practice.

In Chapter 24, formulas and data for the design of crankshafts, curved beams, connecting and coupling rods, piston and piston rings, friction gearing, pawl and ratchet mechanisms, Geneva mechanisms, universal joints, speed reduction gears, variable speed drives, mechanics of vehicles, and unsymmetrical bending and torsion of noncircular cross-section are included. The information given in this chapter on design are helpful while designing machine components of a complete machine. Design equations and other relevant data are given in Chapters from 1 to 23, and 25 to 28.

Chapter 25, on elements of machine tool design, discusses the fundamental principles involved in machine tool design. It deals with the design of components of machine tools and design practices with practical data and guidelines on various aspects of machine tool and design.

A certain minimum working knowledge of the construction and fabrication of major machines such as engine lathe, turret lathe, capstan lathe, milling machine, grinding machine, shaping machine, slotting machine, planing machine, drilling machine, mechanical and hydraulic presses, broaching machine, and N.C. machine etc. are necessary in order to design even a simple machine tool. A designer cannot learn his work from reading books alone. Reading books and journals in his specialized field must be backed by practical design experience in industries.

Chapter 25 deals with design aspects such as design of spindles, slideways, guides, gear boxes for lathes, drilling machines and other machines, beds for lathes, planing columns for drilling machines, milling frames and selection of bearings etc. In order to design the above parts a designer has to study forces acting on single-point metal cutting tool, Merchant's circle for cutting forces, and specific power requirements. Selection of lubricants and cutting fluids for satisfactory working of a machine is very important. The chip formation, feeds, spindle speeds, tool signature and tool life and other information for satisfactory design of a machine tool are provided here to the designer.

A methodical and judicious selection of material with proper heat-treatment in manufacturing of high quality product at low cost is very important in production of any product. An engineer is considered to be a good designer if he is capable of designing a machine tool capable of economic machining, casting, joining and press working of many engineering materials. The design information in the form of figures, tables, charts etc are collected from ASME, BIS, ASTM, SAE, SKF, FAG, ASTME, ISQ, ANSI, DIN standards and are included in this chapter. This chapter also deals with some mechanical presses in addition to other machines used in production processes.

In the machine tool industry, forming processes are very important production processes. Hence forming machineries accounts for more than one-third of the value/number of the machine tool industry. Both mechanical and hydraulic presses are used in this field of the machine tool industry. Chapter 25 also deals with blanking and piercing press, V-bending and U-bending press, deep drawing and redrawing press, extrusion moulding and impact extrusion press, stamping and coining press, and hot upsetting and drop forging press. Some of the equations for calculation of forces and dimensions are presented for the design of press components etc.

Chapter 26, deals with retaining rings and circlips. Retaining rings are fasteners which are used to secure machine components on shafts, holes, and housings. Retaining rings are stamped from thin carbon spring steel or from other materials with good spring properties. There are more than 40 to 50 varieties of retaining rings on the market. The important series of retaining rings are the horseshoe type rings. They are also called by another name as circlips. The varieties of retaining rings listed in Chapter 26 are internal and external retaining rings, inverted internal and external rings, permanent shoulder ring, crescent-shaped ring, E-ring, heavy duty external retaining ring, reinforced E-ring, miniature high-strength retaining ring, two-part interlocking ring, taper-section internal ring, high-strength radially assembled ring, beveled and double-beveled internal and beveled external rings, bowed E-ring, bowed internal and external retaining rings, reinforced external self-locking ring, triangular self-locking ring, and internal and external self-locking rings. Selection of materials for different types of rings are given. Shear strength of ring materials and tensile strength of grooved materials are given in tabular forms. Calculations of axial and radial loads on shafts and groove wall are also included. Tolerances and corner radii or chamfers are tabulated for the use of the designers. The dimensional units and force units are given in both SI and U.S. Customary System units for the benefits of students, teachers, designers, and practicing engineers

Chapter 27, on applied elasticity, is a very important chapter in this Databook. The theory of elasticity can be used to solve simple problems of regular geometrical-shaped elastic solids subjected to known loads. But elastic solids of irregular shapes and subjected to complicated loads cannot be solved by any mathematical methods. In such cases experimental stress analysis techniques such as photo-elasticity, strain gage techniques, Moire techniques, holographic techniques, etc. can be used successfully to find solutions. The soap-film method may be used to find stresses in prismatic bars subject to torsion and bending. The electrical analogy also can be used to solve stresses developed at the fillets of gear teeth, shoulders of stepped shafts etc. when subjected to torsion and bending.

Chapter 27 deals with stresses and strains in two- and three-dimensional problems, stress functions, volume expansion, equilibrium and compatibility equations, and two- and three-dimensional problems in x,y, and polar coordinates. The chapter also deals with principal stresses and strains, Mohr's circle representation of stress and strain, stress-strain relations, thick cylinders subjected to internal and external pressures, curved bars subject to pure bending, rotating disks and cylinders of uniform and variable thickness, plates with circular, elliptical, square and other shapes of cutouts (holes) subject to uniform unaxial, biaxial and pure shear stress, loads at infinity using first principles and complex variable methods, and solving problems using curvilinear coordinates. Several additional topics covered in Chapter 27 are listed in the detailed table of contents.

The author has obtained design data and equations by consulting authentic sources and by deriving and formulating many of the equations himself. This Databook is written with the latest information.

Students, teachers, designers, and practicing engineers have to use a large number of graphs, tables, equations, and other relevant data to find solutions to machine design problems. Students in mechanical engineering are prone to commit errors if they are not properly guided in designing a machine component or machine. A teacher in machine design finds it very difficult to write all equations (empirical and semi-empirical), charts, figures, tables, and other data on a notice board or to give notes on this subject to cover the syllabus in machine design. He has to set more involved machine design problems in examinations giving data and formulas in the question paper, because it is not possible for students to remember all empirical and semi-empirical formulas and other data in machine design while designing a machine or a machine component. Therefore this Databook is primarily written to meet the reference and study needs of the undergraduate and graduate students in mechanical engineering, researchers, designers, practicing engineers, and others.

Authors who have written textbooks in machine design using fps units (i.e. U.S. Customary System units) can also consult this *Machine Design Databook* with confidence for SI equivalents of empirical and semiempirical formulas and other data which have been drawn from different standards and sources. These equations and data in SI units in this Databook have been tested with numerical examples before incorporating them in the Databook over a period of 20 years during which author has taught machine design to students at undergraduate and graduate level.

Mechanical designers, researchers, and practicing engineers have to design equipment, mechanical devices, and sometime the whole machines in practice. Researchers have to design some component of equipment which they are using in their day-to-day research work. The same is true in case of engineers in industries. In such a situation, the designer, the researcher, or practicing engineer has to refer to source books such as this *Machine Design Databook* from which reliable and updated information can be drawn.

This Databook refers to many standards and data which are in vogue at present in the world. They may change with time and more progress in technology. This has to be taken into consideration in using the standards and data in this Databook.

In a work of this nature there are bound to be errors, and the author would be grateful if these are brought to his notice for future guidance. Any suggestions, for the improvement of this Databook will be gratefully received.

It is sincerely hoped that this Databook will be useful to students, teachers, designers, practicing engineers, and researchers.

K. Lingaiah

ACKNOWLEDGMENTS

The author is grateful to McGraw-Hill for undertaking the complex work of publishing this revised second edition. The author is also grateful to Mr. Robert W. Hauserman who was then Senior Editor at McGraw-Hill for sponsoring the publication of the first edition of the Databook. The author is also grateful to Miss Kimberly A. Golf, Senior Editing Supervisor, Miss Julia A. Dietz, and other supporting staff of McGraw-Hill for having helped and encouraged the author in bringing out this major work.

I am grateful to Ms. Linda R. Ludewig, Mechanical Engineering Editor at McGraw-Hill, who initiated the revision of this *Machine Design Databook*. Mr. Kenneth P. McCombs, Senior Editor, Mechanical and Chemical Engineering, McGraw-Hill deserves a special mention and thanks for his tireless effort. The author also grateful to all supporting staff of McGraw-Hill for having helped the author to complete the work.

The author owes a debt of gratitude to late Professor B.R. Narayana Iyengar, who was a guru, a guide, and a source of inspiration to the author.

The author is grateful to his parents Kenchaiah and Madamma, his wife M.P. Madamma, his children L. Susheela, L. Nagarathna, L. Vasanth Kumar, L. Suma, and L. Vivekananda but for whose patience, constant support and encouragement and help, this publication would have not been possible.

The author owes a debt of gratitude to the Bangalore University and the University Visvesvaraya College of Engineering, Bangalore where the author has taught the students at undergraduate and graduate level in Machine Design as a lecturer, reader and Professor of Mechanical Engineering, Head of the Department, Dean of Engineering and Principal from 1958 up to his retirement. At present he is working on a university level book writing project at Bangalore University sanctioned by University Grants Commission, New Delhi.

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9. Butterworth-Heinemann, Oxford.
10. Mir Publishers, Moscow.
11. Machine Design, Cleveland, Ohio.
12. DIN-Deutsches Institut fur Normung e.V., Berlin, Germany.
13. Society of Automotive Engineers, Inc., Warrendale, Pennsylvania.
14. CBS Publishers and Distributors, Delhi.
15. The American Society of Mechanical Engineers, New York.

16. MAAG Gear Co., Ltd, Zurich, Switzerland.
17. American Gear Manufacturers Association, Alexandria, Virginia.
18. Bureau of Indian Standards, Manak Bhavan, New Delhi.
19. The Gleason Works, Rochester, New York.
20. International Organization for Standards, Geneva, Switzerland.
21. Det Norske Veritas Classification AS, Hovik, Norway.
22. American Society for Metals, Metals Park, Ohio.
23. Associated Spring, Barnes Group Inc., Bristol, Connecticut.
24. Van Nostrand Reinhold Company, New York.
25. Edward Arnold (Publishers) Ltd, Great Britain.

A large number of extracts from the AGMA, ISO, BIS, BSI, ASME and DIN standards and Gleason Works, etc., have been incorporated in this Databook to make the book more usefu1 to students, teachers, designers, and practicing engineers. Also included are standards from Det Norske Veritas Classification, *MAAG Gear Handbook*, and information from FAG and SKF bearing catalogues.

The author gratefully expresses his gratitude to various other publishers of books and journals and their authors for permission to make use of the materials from their books and technical Journals.

Finally the author wholeheartedly thanks all those persons who have helped directly or indirectly in writing this Databook whose names are not mentioned here.

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CHAPTER
1

PROPERTIES OF ENGINEERING MATERIALS

SYMBOLS[5,6]

a	area of cross section, m^2 (in^2)*
	original area of cross section of test specimen, mm^2 (in^2)
A_j	area of smallest cross section of test specimen under load F_j, m^2 (in^2)
A_f	minimum area of cross section of test specimen at fracture, m^2 (in^2)
A_0	original area of cross section of test specimen, m^2 (in^2)
A_r	percent reduction in area that occurs in standard test specimen
Bhn	Brinell hardness number
d	diameter of indentation, mm
	diameter of test specimen at necking, m (in)
D	diameter of steel ball, mm
E	modulus of elasticity or Young's modulus, GPa [Mpsi (Mlb/in^2)]
f_ε	strain fringe (fri) value, μm/fri (μin/fri)
f_σ	stress fringe value, kN/m fri (lbf/in fri)
F	load (also with subscripts), kN (lbf)
G	modulus of rigidity or torsional or shear modulus, GPa (Mpsi)
H_B	Brinell hardness number
l_f	final length of test specimen at fracture, mm (in)
l_j	gauge length of test specimen corresponding to load F_j, mm (in)
l_0	original gauge length of test specimen, mm (in)
Q	figure of merit, fri/m (fri/in)
R_B	Rockwell B hardness number
R_C	Rockwell C hardness number
ν	Poisson's ratio
σ	normal stress, MPa (psi)

* The units in parentheses are **US Customary units** [e.g., fps (foot-pounds-second)].

σ_b	transverse bending stress, MPa (psi)
σ_c	compressive stress, MPa (psi)
σ_s	strength, MPa (psi)
σ_t	tensile stress, MPa (psi)
σ_{sf}	endurance limit, MPa (psi)
σ'_{sf}	endurance limit of rotating beam specimen or R R Moore endurance limit, MPa (psi)
σ'_{sfa}	endurance limit for reversed axial loading, MPa (psi)
σ'_{sfb}	endurance limit for reversed bending, MPa (psi)
σ_{sc}	compressive strength, MPa (psi)
σ_{su}	tensile strength, MPa (psi)
σ_u	ultimate stress, MPa (psi)
σ_{uc}	ultimate compressive stress, MPa (psi)
σ_{ut}	ultimate tensile stress, MPt (psi)
$\sigma_{\widehat{su}}$	ultimate strength, MPA (psi)
σ_{suc}	ultimate compressive strength, MPa (psi)
σ_{sut}	ultimate tensile strength, MPa (psi)
σ_y	yield stress, MPa (psi)
σ_{yc}	yield compressive stress, MPa (psi)
σ_{yt}	yield tensile stress, MPa (psi)
σ_{syc}	yield compressive strength, MPa (psi)
σ_{syt}	yield tensile strength, MPa (psi)
τ	torsional (shear) stress, MPa (psi)
τ_s	shear strength, MPa (psi)
τ_u	ultimate shear stress, MPa (psi)
τ_{su}	ultimate shear strength, MPa (psi)
τ_y	yield shear stress, MPa (psi)
τ_{sy}	yield shear strength, MPa (psi)
τ'_{sf}	torsional endurance limit, MPa (psi)

SUFFIXES

a	axial
b	bending
c	compressive
f	endurance
s	strength properties of material
t	tensile
u	ultimate
y	yield

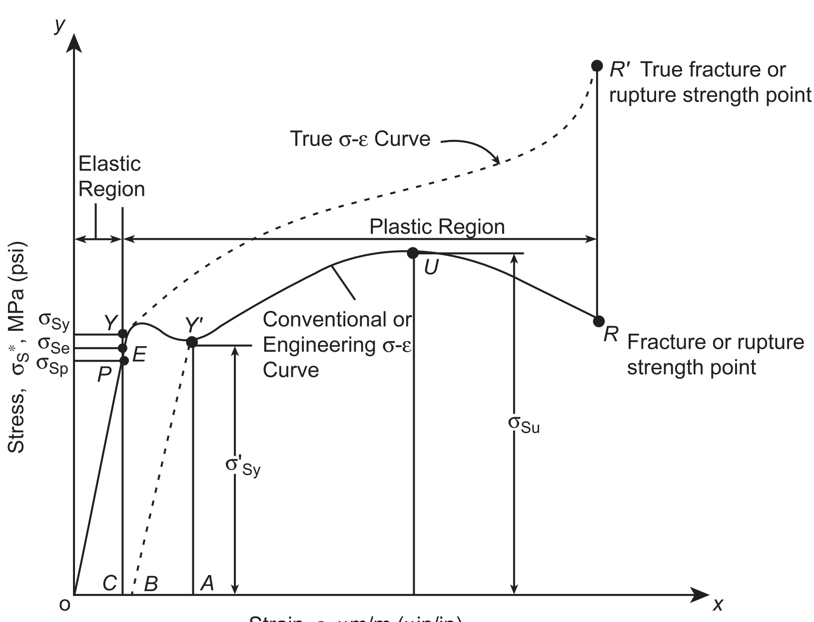
ABBREVIATIONS

AISI	American Iron and Steel Institute
ASA	American Standards Association
AMS	Aerospace Materials Specifications
ASM	American Society for Metals
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing Materials
BIS	Bureau of Indian Standards
BSS	British Standard Specifications
DIN	Deutsches Institut für Normung
ISO	International Standards Organization

SAE	Society of Automotive Engineers
UNS	Unified Numbering system

Note: σ and τ with subscript s designates strength properties of material used in the design which will be used and observed throughout this *Machine Design Data Handbook*. Other factors in performance or in special aspects are included from time to time in this chapter and, being applicable only in their immediate context, are not given at this stage.

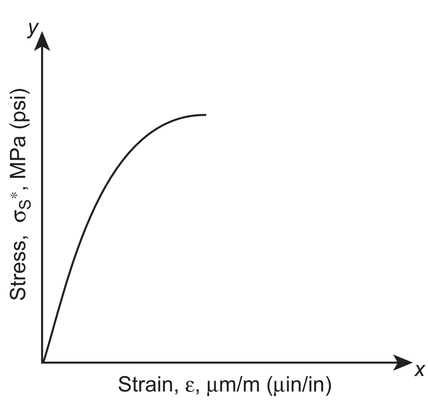
Particular	Formula
For engineering stress-strain diagram for ductile steel, i.e., low carbon steel	Refer to Fig. 1-1
For engineering stress-strain diagram for brittle material such as cast steel or cast iron	Refer to Fig. 1-2
The nominal unit strain or engineering strain	$\varepsilon = \dfrac{l_f - l_0}{l_0} = \dfrac{\Delta l}{l_0} = \dfrac{l_f}{l_0} - 1 = \dfrac{A_0 - A_f}{A_0}$ (1-1) where l_f = final gauge length of tension test specimen, l_0 = original gauge length of tension test specimen.
The numerical value of strength of a material	$\sigma_s = \dfrac{F}{A}$ (1-2) where subscript s stands for strength.



Point P is the proportionality limit. Y is the upper yield limit. E is the elastic limit. Y' is the lower yield point. U is the ultimate tensile strength point. R is the fracture or rupture strength point. R' is the true fracture or rupture strength point.

FIGURE 1-1 Stress-strain diagram for ductile material.
* Subscript s stands for strength.

Particular	Formula
The nominal stress or engineering stress	$$\sigma = \frac{F}{A_0} \tag{1-3}$$ where F = applied load.
The true stress	$$\sigma_{tru} = \sigma' = \frac{F}{A_f} \tag{1-4}$$ where A_f = actual area of cross section or instantaneous area of cross-section of specimen under load F at that instant.
Bridgeman's equation for actual stress (σ_{act}) during r radius necking of a tensile test specimen	$$\sigma_{act} = \frac{\sigma_{cal}}{\left(1 + \frac{4r}{d}\right)\left[\ln\left(1 + \frac{d}{4r}\right)\right]} \tag{1-5}$$
The true strain	$$\varepsilon_{tru} = \varepsilon' = \frac{\Delta l_1}{l_0} + \frac{\Delta l_2}{l_0 + \Delta l_1} + \frac{\Delta l_3}{l_0 + \Delta l_1 + \Delta l_2} + \cdots \tag{1-6a}$$ $$= \int_{l_0}^{l_f} \frac{dl_i}{l_i} \tag{1-6b}$$
Integration of Eq. (1-6) yields the expression for true strain	$$\varepsilon_{tru} = \ln\left(\frac{l_f}{l_0}\right) \tag{1-7}$$
From Eq. (1-1)	$$\frac{l_f}{l_0} = 1 + \varepsilon \tag{1-8}$$
The relation between true strain and engineering strain after taking natural logarithm of both sides of Eq. (1-8)	$$\ln\left(\frac{l_f}{l_0}\right) = \ln(1+\varepsilon) \quad \text{or} \quad \varepsilon_{tru} = \ln(1+\varepsilon) \tag{1-9}$$
Eq. (1-9) can be written as	$$\varepsilon = e^{\varepsilon_{tru}} - 1 \tag{1-10}$$



There is no necking at fracture for brittle material such as cast iron or low cast steel.

FIGURE 1-2 Stress-strain curve for a brittle material.

Particular	Formula
Percent elongation in a standard tension test specimen	$\varepsilon_{100} = \dfrac{l_f - l_0}{l_0}(100)$ (1-11)
Reduction in area that occurs in standard tension test specimen in case of ductile materials	$A_r = \dfrac{A_0 - A_f}{A_0}$ (1-12)
Percent reduction in area that occurs in standard tension test specimen in case of ductile materials	$A_{r100} = \dfrac{A_0 - A_f}{A_0}(100)$ (1-13)
For standard tensile test specimen subject to various loads	Refer to Fig. 1-3.

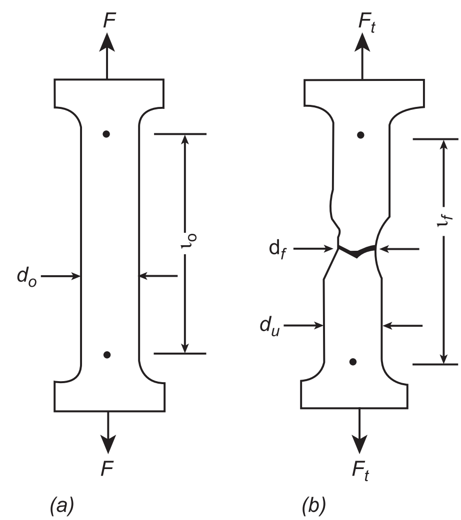


FIGURE 1-3 A standard tensile specimen subject to various loads.

Particular	Formula
The standard gauge length of tensile test specimen	$l_0 = 6.56\sqrt{a}$ (1-14)
The volume of material of tensile test specimen remains constant during the plastic range which is verified by experiments and is given by	$A_0 l_0 = A_f\, l_f$ or $\dfrac{l_f}{l_0} = \dfrac{A_0}{A_f} = \dfrac{d_0^2}{d_f^2}$ (1-15)
Therefore the true strain from Eqs. (1-7) and (1-15)	$\varepsilon_{tru} = \ln\left(\dfrac{A_0}{A_f}\right) = \ln\dfrac{l_f}{l_0} = 2\ln\dfrac{d_0}{d_f}$ (1-16) where d_f = minimum diameter in the gauge length l_f of specimen under load at that instant, A_r = minimum area of cross section of specimen under load at that instant.
The true strain at rupture, which is also known as the true fracture strain or ductility	$\varepsilon_{ftru} = \ln\left(\dfrac{1}{1 - A_r}\right)$ (1-17) where A_f is the area of cross-section of specimen at fracture.

Particular	Formula
	Refer to Table 1-1A for values of ε_{ftru} of steel and aluminum.
From Eqs. (1-9) and (1-16)	$\frac{A_0}{A_f} = 1 + \varepsilon \quad \text{or} \quad A_f = \frac{A_0}{1+\varepsilon}$ (1-18)
Substituting Eq. (1-18) in Eq. (1-4) and using Eq. (1-3) the true stress	$\sigma_{tru} = \sigma(1+\varepsilon) = \sigma e^{\varepsilon_{tru}}$ (1-19)
From experimental results plotting true-stress versus true-strain, it was found that the equation for plastic stress-strain line, which is also called the strain-strengthening equation, the true stress is given by	$\sigma_{tru} = \sigma_0 \varepsilon_{trup}^n$ (1-20) where σ_0 = strength coefficient, n = strain hardening or strain strengthening exponent, ε_{trup} = true plastic strain. Refer to Table 1-1A for σ_0 and n values for steels and other materials.
The load at any point along the stress-strain curve (Fig 1-1)	$F = \sigma_s A_0$ (1-21)
The load-strain relation from Eqs. (1-20) and (1-2)	$F = \sigma_0 A_0 \varepsilon_{tru}^n e^{-\varepsilon_{tru}}$ (1-22)
Differentiating Eq. (1-22) and equating the results to zero yields the true strain equals to the strain hardening exponent which is the instability point	$\varepsilon_u = n$ (1-23)
The stress on the specimen which causes a given amount of cold work W	$\sigma_w = \sigma_0(\varepsilon_w)^n = \frac{F_w}{A_w}$ (1-24) where A_w = actual cross-sectional area of the specimen, F_w = applied load.
The approximate yield strength of the previously cold-worked specimen	$(\sigma_{sy})_w = \frac{F_w}{A'_w}$ (1-25) where $A_w = A'_w$ = the increased cross-sectional area of specimen because of the elastic recovery that occurs when the load is removed.
The approximate yield strength since $A'_w = A_w$	$(\sigma_{sy})_w = \frac{F_w}{A'_w} \approx \sigma_w$ (1-26)
By substituting Eq. (1-26) into Eq. (1-24)	$(\sigma_{sy})_w = \sigma_0(\varepsilon_w)^n$ (1-27)
The tensile strength of a cold worked material	$(\sigma_{su})_w = \frac{F_u}{A'_w}$ (1-28) where $A_w = A_u$, $F_u = A_0(\sigma_{su})_0$, σ_{su} = tensile strength of the original non-cold worked specimen, A_0 = original area of the specimen.
The percent cold work associated with the deformation of the specimen from A_0 to A'_w	$W = \frac{A_0 - A'_w}{A_0}(100) \quad \text{or} \quad w = \frac{A_0 - A'_w}{A_0}$ (1-29) where $w = \frac{W}{100}$

Particular	Formula
For standard tensile specimen at stages of loading A'_w is given by equation	$A'_w = A_0(1 - w)$ (1-30)
Expression for $(\sigma_{su})_w$ after substituting Eq. (1-28)	$(\sigma_{su})_w = \dfrac{(\sigma_{su})_0}{1 - w}$ (1-31)
Eq. (1-31) can also be expressed as	$(\sigma_{su})_w = (\sigma_{su})_0 e^{\varepsilon_{tru}}$ (1-32) Valid for $A_w \le A_u$ or $\varepsilon_w \le \varepsilon_u$.
The modulus of toughness	$T_m = \int_0^{\varepsilon_r} \sigma_s d\varepsilon$ (1-33a) $\approx \dfrac{\sigma_s + \sigma_{su}}{2} \varepsilon_r$ (1-34b) where $\varepsilon_r = \varepsilon_u$ = strain associated with incipient fracture.

HARDNESS

Particular	Formula
The Vicker's hardness number (H_V) or the diamond pyramid hardness number (H_p)	$H_V = \dfrac{2F \sin(\alpha/2)}{d^2} = \dfrac{1.8544F}{d^2}$ (1-35) where F = load applied, kgf, α = face angle of the pyramid, 136°, d = diagonal of the indentation, mm, H_V in kgf/mm^2.
The Knoop hardness number	$H_K = \dfrac{F}{0.07028d^2}$ (1-36) where d = length of long diagonal of the projected area of the indentation, mm, F = load applied, kgf, 0.07028 = a constant which depends on one of angles between the intersections of the four faces of a special rhombic-based pyramid industrial diamond indenter 172.5° and the other angle is 130°, H_K in kgf/mm^2.
The Meyer hardness number, H_M	$H_M = \dfrac{4F}{\pi d^2/4}$ (1-37) where F = applied load, kgf, d = diameter of indentation, mm, H_M in kgf/mm^2.
The Brinell hardness number H_B	$H_B = \dfrac{2F}{\pi D[D - \sqrt{D^2 - d^2}]}$ (1-38) where F in kgf, d and D in mm, H_B in kgf/mm^2.
The Meyer's strain hardening equation for a given diameter of ball	$F = Ad^p$ (1-39) where F = applied load on a spherical indenter, kgf, d = diameter of indentation, mm, p = Meyer strain-hardening exponent.

Particular	Formula
The relation between the diameter of indentation d and the load F according to Datsko[1,2]	$F = 18.8d^{2.53}$ (1-40)
The relation between Meyer strain-hardening exponent p in Eq. (1-39) and the strain-hardening exponent n in the tensile stress-strain Eq. $\sigma = \sigma_0 \varepsilon^n$	$p - 2 = n$ (1-41) where $p = 2.25$ for both annealed pure aluminum and annealed 1020 steel, $p = 2$ for low work hardening materials such as pH stainless steels and all cold rolled metals, $p = 2.53$ experimentally determined value of 70-30 brass.
The ratio of the tensile strength (σ_{su}) of a material to its Brinell hardness number (H_B) as per experimental results conducted by Datsko[1,2]	$K_B = \dfrac{\sigma_{su}}{H_B}$ (1-42)
For the plot of ratio of $(\sigma_{su}/H_B) = K_B$ against the strain-strengthening exponent n* (1)	Refer to Fig. 1-4 for K_B *vs* n for various ratios of (d/D).

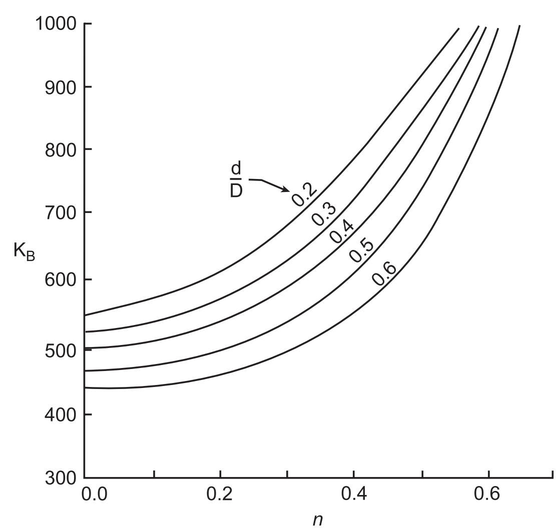


FIGURE 1-4 Ratio of $(\sigma_{su}/H_B) = K_B$ *vs* strain strengthening exponent n.

Particular	Formula
The relationship between the Brinell hardness number H_B and Rockwell C number R_C	$R_C = 88H_B^{0.162} - 192$ (1-43)
The relationship between the Brinell hardness number H_B and Rockwell B number R_B	$R_B = \dfrac{H_B - 47}{0.0074H_B + 0.154}$ (1-44)

* *Courtesy*: Datsko, J., *Materials in Design and Manufacture*, J. Datsko Consultants, Ann Arbor, Michigan, 1978, and *Standard Handbook of Machine Design*, McGraw-Hill Book Company, New York, 1996.

Particular	Formula
The approximate relationship between ultimate tensile strength and Brinell hardness number of carbon and alloy steels which can be applied to steels with a Brinell hardness number between $200H_B$ and $350H_B$ only[1,2]	$\sigma_{sut} = 3.45H_B$ MPa **SI** (1-45a) $= 500H_B$ psi **USCS** (1-45b)
The relationship between the minimum ultimate strength and the Brinell hardness number for steels as per ASTM	$\sigma_{sut} = 3.10H_B$ MPa **SI** (1-46a) $= 450H_B$ psi **USCS** (1-46b)
The relationship between the minimum ultimate strength and the Brinell hardness number for cast iron as per ASTM	$\sigma_{sut} = 1.58H_B - 86.2$ MPa **SI** (1-47a) $= 230H_B - 12500$ psi **USCS** (1-47b)
The relationship between the minimum ultimate strength and the Brinell hardness number as per SAE minimum strength	$\sigma_{sut} = 2.60H_B - 110$ MPa **SI** (1-48a) $= 237.5H_B - 16000$ psi **USCS** (1-48b)
In case of stochastic results the relation between H_B and σ_{sut} for steel based on Eqs. (1-45a) and (1-45b)	$\sigma_{sut} = (3.45, 0.152)H_B$ MPa **SI** (1-49a) $= (500, 22)H_B$ psi **USCS** (1-49b)
In case of stochastic results the relation between H_B and σ_{sut} for cast iron based on Eqs. (1-47a) and (1-47b)	$\sigma_{sut} = 1.58H_B - 62 + (0, 10.3)$ MPa **SI** (1-50a) $= 230H_B - 9000 + (0, 1500)$ psi **USCS** (1-50*b*)
Relationships between hardness number and tensile strength of steel in SI and US Customary units [7]	Refer to Fig. 1.5.
The approximate relationship between ultimate shear stress and ultimate tensile strength for various materials	$\tau_{su} = 0.82\sigma_{sut}$ for wrought steel (1-51a) $\tau_{su} = 0.90\sigma_{sut}$ for malleable iron (1-51b) $\tau_{su} = 1.30\sigma_{sut}$ for cast iron (1-51c) $\tau_{su} = 0.90\sigma_{sut}$ for copper and copper alloy (1-51d) $\tau_{su} = 0.65\sigma_{sut}$ for aluminum and aluminum alloys (1-51e)
The tensile yield strength of stress-relieved (not cold-worked) steels according to Datsko[1,2]	$\sigma_{sy} = (0.072\sigma_{sut} - 205)$ MPa SI (1-52a) $= 1.05\sigma_{sut} - 30$ kpi **USCS** (1-52b)
The equation for tensile yield strength of stress-relieved (not cold-worked) steels in terms of Brinell hardness number H_B according to Datsko (2)	$\sigma_{sy} = (3.62H_B - 205)$ MPa SI (1-53a) $= 525H_B - 30$ kpi **USCS** (1-53b)
The approximate relationship between shear yield strength (τ_{sy}) and yield strength (tensile) σ_{sy}	$\tau_{sy} = 0.55\sigma_{sy}$ for aluminum and aluminum alloys (1-54a) $\tau_{sy} = 0.58\sigma_{sy}$ for wrought steel (1-54b)

Particular	Formula

The approximate relationship between endurance limit (also called *fatigue limit*) for reversed bending polished specimen based on 50 percent survival rate and ultimate strength for nonferrous and ferrous materials

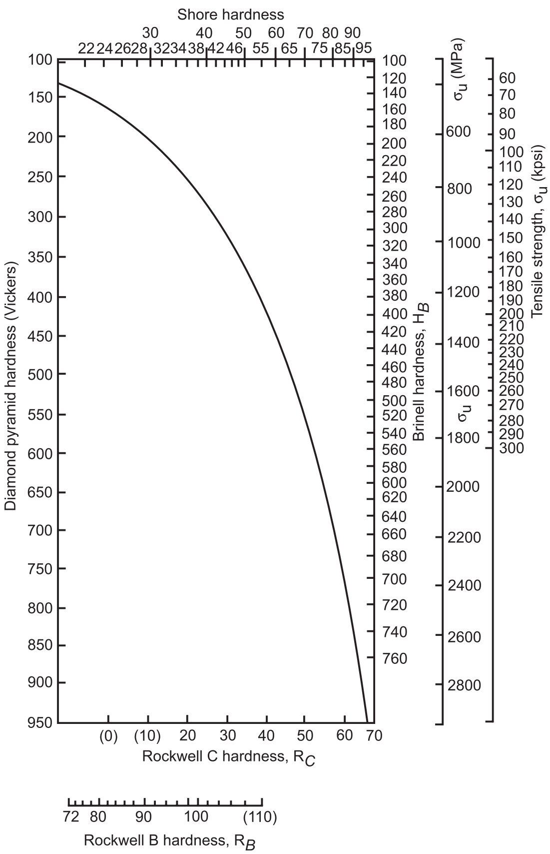


FIGURE 1-5 Conversion of hardness number to ultimate tensile strength of steel σ_{sut}, MPa (kpsi). (*Technical Editor Speaks, courtesy of International Nickel Co., Inc., 1943.*)

For students' use

$\sigma'_{sfb} = 0.50\sigma_{sut}$ for wrought steel having $\sigma_{sut} < 1380$ MPa (200 kpsi) (1-55)

$\sigma'_{sfb} = 690$ MPa for wrought steel having $\sigma_{sut} > 1380$ MPa (1-56a)

$\sigma'_{sfb} = 100$ kpsi for wrought steel having $\sigma_{sut} > 200$ kpsi **USCS** (1-56b)

For practicing engineers' use

$\sigma'_{sfb} = 0.35\sigma_{sut}$ for wrought steel having $\sigma_{sut} < 1380$ MPa (200 kpsi) (1-57)

$\sigma'_{sfb} = 550$ MPa for wrought steel having $\sigma_{sut} > 1380$ MPa **SI** (1-58a)

$\sigma'_{sfb} = 80$ kpsi for wrought steel having $\sigma_{sut} > 200$ kpsi **USCS** (1-58b)

$\sigma'_{sfb} = 0.45\sigma_{sut}$ for cast iron and cast steel when $\sigma_{sut} \leq 600$ MPa (88 kpsi) (1-59a)

$\sigma'_{sfb} = 275$ MPa for cast iron and cast steel when $\sigma_{sut} > 600$ MPa **SI** (1-60a)

$\sigma'_{sfb} = 40$ kpsi for cast iron and cast steel when $\sigma_{sut} > 88$ kpsi **USCS** (1-60b)

$\sigma'_{sfb} = 0.45\sigma_{sut}$ for copper-based alloys and nickel-based alloys (1-61)

$\sigma'_{sfb} = 0.36\sigma_{sut}$ for wrought aluminum alloys up to a tensile strength of 275 MPa (40 kpsi) based on 5×10^8 cycle life (1-62)

$\sigma'_{sfb} = 0.16\sigma_{sut}$ for cast aluminum alloys up to tensile strength of 300 MPa (50 kpsi) based on 5×10^8 cycle life (1-63)

$\sigma'_{sfb} = 0.38\sigma_{sut}$ for magnesium casting alloys and magnesium wrought alloys based on 10^6 cyclic life (1-64)

Particular	Formula
The relationship between the endurance limit for reversed axial loading of a polished, unnotched specimen and the reversed bending for steel specimens	$\sigma'_{sfa} = 0.85\sigma'_{sfb} = 0.43\sigma_{sut}$ (1-65)
The relationship between the torsional endurance limit and the reversed bending for reversed torsional tested polished unnotched specimens for various materials	$\tau'_{sf} = 0.58\sigma'_{sfb} = 0.29\sigma_{sut}$ for steel (1-66a) $\tau'_{sf} \approx 0.8\sigma'_{sfb} \approx 0.32\sigma_{sut}$ for cast iron (1-66b) $\tau'_{sf} \approx 0.48\sigma'_{sfb} \approx 0.22\sigma_{sut}$ for copper (1-66c)
For additional information or data on properties of engineering materials	Refer to Tables 1-1 to 1-48

WOOD

Specific gravity, G_m, of wood at a given moisture condition, m, is given by	$G_m = \dfrac{W_0}{W_m}$ (1-67) where W_0 = weight of the ovendry wood, N (lbf), W_m = weight of water displaced by the sample at the given moisture condition, N (lbf).
The weight density of wood, D (unit weight) at any given moisture content	$W = \dfrac{\text{weight of ovendry wood and the contained water}}{\text{volume of the piece at the same moisture content}}$ (1-68)
Equation for converting of weight density D_1 from one moisture condition to another moisture condition D_2	$D_2 = D_1 \dfrac{100 + M_2}{100 + M_1 + 0.0135D_1(M_2 - M_1)}$ (1-69) where D_1 = known weight density for same moisture condition M_1, kN/m^2 (lbf/ft^2), D_2 = desired weight density at a moisture condition M_2, kN/m^2 (lbf/ft^2). M_1 and M_2 are expressed in percent.
For typical properties of wood of clear material as per ASTM D 143	Refer to Table 1-47.

TABLE 1-1
Hardness conversion (approximate)

Brinell 29.42 kN (3000 kgf) load 10 mm ball			Rockwell hardness number					Tensile strength, σ_{sut} approximate	
Diameter (mm)	Hardness number	Vickers or Firth hardness number	*A* scale 0.588 kN (60 kgf) load	*B* scale 0.98 kN (100 kgf) load	*C* scale 1.47 kN (150 kgf) load	15-*N* scale 0.147 kN (15 kgf) load	Shore scleroscope hardness number	MPa	kpsi
2.25	745	840	84		65	92	91	2570	373
2.30	712	783	83		64	92	87	2455	356
2.35	682	737	82		62	91	84	2350	341
2.40	653	697	81		60	90	81	2275	330
2.45	627	667	81		59	90	79	2227	323
2.50	601	640	80		58	89	77	2192	318
2.55	578	615	79		57	88	75	2124	309
2.60	555	591	78		55	88	73	2020	293
2.65	534	569	78		54	87	71	1924	279
2.70	514	547	77		52	87	70	1834	266
2.75	495	528	76		51	86	68	1750	254
2.80	477	508	76		50	85	66	1675	243
2.85	461	491	75		49	85	65	1620	235
2.90	444	472	74		47	84	63	1532	222
2.95	429	455	73		46	83	61	1482	215
3.00	415	440	73		45	83	59	1434	208
3.05	401	425	72		43	82	58	1380	200
3.10	388	410	71		42	81	56	1338	194
3.15	375	396	71		40	81	54	1296-	188
3.20	363	383	70		39	80	52	1255	182
3.25	352	372	69	110	38	79	51	1214	176
3.30	341	360	69	109	37	79	50	1172	170
3.35	331	350	68	109	36	78	48	1145	166
3.40	321	339	68	108	34	77	47	1103	160
3.45	311	328	67	108	33	77	46	1069	155
3.50	302	319	66	107	32	76	45	1042	151
3 55	293	309	66	106	31	76	43	1010	146
3.60	285	301	65	106	30	75	42	983	142
3.65	277	292	65	105	29	74	41	955	138
3.70	269	284	64	104	28	74	40	928	134
3.75	262	276	64	103	27	73	39	904	131
3.80	255	269	63	102	25	73	38	875	127
3.85	248	261	63	101	24	72	37	855	124
3.90	241	253	62	100	23	71	36	832	120
3.95	235	247	61	99	22	70	35	810	117
4.00	229	241	61	98	21	70	34	790	114
4.05	223	234		97	19			770	111
4.10	217	228		96	18		33	748	108
4.15	212	222		96	16		32	730	106
4.20	207	218		95	15		31	714	103
4.25	201	212		94	14			690	100
4.30	197	207		93	13		30	680	98
4.35	192	202		92	12		29	662	96
4.40	187	196		91	10			645	93

TABLE 1-1
Hardness conversion (approximate) (*Cont.*)

Brinell 29.42 kN (3000 kgf) load 10 mm ball		Vickers or Firth hardness number	Rockwell hardness number				Shore scleroscope hardness number	Tensile strength, σ_{sut} approximate	
Diameter (mm)	Hardness number		*A* scale 0.588 kN (60 kgf) load	*B* scale 0.98 kN (100 kgf) load	*C* scale 1.47 kN (150 kgf) load	15-*N* scale 0.147 kN (15 kgf) load		MPa	kpsi
4.45	183	192		90	9		28	631	91
4.50	179	188		89	8		27	617	89
4.55	174	182		88	7			600	87
4.60	170	178		87	5		26	585	85
4.65	167	175		86	4			576	83
470	163	171		85	3		25	562	81
4.80	156	163		83	1		24	538	78
4.90	149	156		81			23	514	74
5.00	143	150		79			22	493	71
5.10	137	143		76			21	472	68
5.20	131	137		74				451	65
5.30	126	132		72			20	435	63
5.40	121	127		70			19	417	60
5.50	116	122		68			18	400	58
5.60	111	117		65			17	383	55

TABLE 1-1A
Mechanical properties of some metallic materials

Material	Brinell hardness H_B	Process/ Condition	Ultimate strength, σ_{sut}		Yield strength, σ_{sy}		Stress at fracture, σ_f		Reduction in area, A_f	True strain at fracture	Strain hard- ing exponent	Strength coefficient, σ_0	
			MPa	kpsi	MPa	kpsi	MPa	kpsi	%	ε_f	n	MPa	kpsi
						Steel							
RQC-100[a]	290	HR[b] Plate	931	135	883	128	1331	193	67	1.02	0.06	1172	170
1005-1009	125	CD[c] Sheet	414	60	400	58	841	122	64	1.02	0.05	524	76
1005-1009	90	HR Sheet	345	50	262	38	848	123	80	1.60	0.16	531	77
1015	80	Normalized	414	60	228	33	724	105	68	1.14	0.26		
1020[d]	108	HR Plate	441	64	262	38	710	103	62	0.96	0.19	738	107
1045[e]	225	Q and T[f]	724	105	634	92	1227	178	65	1.04	0.13	1145	166
1045[e]	410	Q and T	1448	210	1365	198	1862	270	51	0.72	0.08	2082	302
5160	430	Q and T	1669	242	1531	222	1931	280	42	0.87	0.06	2124	308
9262	260	Annealed	924	134	455	66	1041	151	14	0.16	0.22	1744	253
9262	410	Q and T	1565	227	1379	200	1855	269	32	0.38	0.06		
950	150	HR Plate	531	77	311	48	1000	145	72	1.24	0.19	903	131
						Aluminum:							
2024-T351		ST, SH[g]	469	68	379	55	558	81	25	0.28	0.03	455	66
2024-T4		ST and RT age[h]	476	69	303	44	636	92	35	0.43	0.20	807	117
7075-T6		ST and AA[i]	579	84	469	68	745	108	33	0.41	0.11	827	120

[a] Tradename, Bethlehem steel Corp. Rolled quenched and tempered carbon steel. Used in structural, heavy applications machinery. [b] Hot-rolled. [c] cold-rolled. [d] low carbon, common machining steels. [e] Bar stock, medium carbon high-strength machining steel. [f] Quenched and tempered. [g] Solution treated, strain hardened. [h] Solution treated and RT age. [i] Solution treated and artificially aged.
Source: SAE j1099, Technical Report on Fatigue properties, 1975.

TABLE 1-1B
Mechanical properties of some typical metallic materials

			Ultimate tensile strength, σ_{sut}		Yield strength: Tensile, σ_{syt}		Yield strength: Compressive, σ_{syc}		Shear (torsional) strength: Ultimate, τ_{su}		Shear (torsional) strength: Yield, τ_{sy}		Fatigue limit, σ_{sf}		Young's modulus, E		Modulus of rigidity, G		Fracture toughness, K_{IC}		Reduction in area	True strain at fracture,
Material	Form	Condition/Process	MPa	kpsi	MPa	kpsi	MPa	kpsi	MPa	kpsi	MPa	kpsi	MPa	kpsi	GPa	Mpsi	GPa	Mpsi	GPa	Mpsi	A, %	ε_f
Steel:																						
1016		CD 0%	455	66	275	40							240	35[d]							70	1.20
		CD 30%	620	90	585	85							315	46[d]							62	0.97
		CD 60%	710	102	605	88							350	51[d]							54	0.78
		CD 80%	790	115	660	96							365	53[d]							26	0.30
1020	25 mm (1 in) bar or plate	HR	448	65	331	48							241	35[d]							59	0.89
1030	25 mm (1 in) WQ bar or plate	(1200°F)	586	85	441	64					241	35	296	43	204	29.6	83	12.0			70	1.20
1040	25 mm (1 in) bar	Annealed	517	75	352	51							269	39							57	0.84
		HR	621	90	414	60							296	43[a]							50	0.69
		CD 20%	805	117	670	97							370	54[d]							44	0.58
		CD 50%	965	140	855	124							410	60[d]							25	0.33
1050	25 mm (1 in) bar	Annealed	634	92	365	53							365	53			79	11.4			40	0.51
		CD 20% + s.r.2h (900°F	876	127	696	101							427	62[d]							31	0.37
4130	25 mm (1 in) bar	WQ + (1200°F)	814	118	703	102	724	105					490	71							64	1.02
4340	25 mm (1 in) bar	OQ + (1000 °F)	1262	183	1172	170	1310	190	876	127	752	109	669	97	207	30.0	81	11.7	110	100	52	0.73
		OQ + (800 °F)	1531	200	1379	200	1517	220	1007	146	855	124	469	68					75	68	47	0.63
18% Ni maraging																						
200	L plate	Aged 482°C	1540	225	1480	215							690	100							55	0.80
250	L plate	Aged 482°C	1760	256	1630	237							690	100							62	0.97
300	L plate	Aged 482°C	1980	288	1920	279							760	110							50	0.69

[a] A description of the materials and typical uses follows the table.
[b] CD = cold drawn (the percentage reduction in area); HR = hot rolled; OQ = oil quenched; WQ = water quenched (temperature following is the tempering temperature); s.r. = stress relieved.
[c] Smooth-specimen rotating-beam results, unless noted A (= axial).
[d] 10^6 cycles.

Source: Extracted from Kenneth S. Edwards, Jr, and Robert B. McKee, *Fundamentals of Mechanical Component Design*, McGraw-Hill, Inc., 1991, which is drawn from the *Structural Alloys Handbook*, published by the Metals and Ceramics Information Center, Battelle Memorial Institute, Columbus, Ohio, 1985.

TABLE 1-2
Poisson's ratio (ν)

Material	ν	Material	ν
Aluminium, cast	0.330	Molybdenum	0.293
Aluminium, drawn	0.348	Monel metal	0.320–0.370
Beryllium copper	0.285	Nickel, soft	0.239
Brass	0.340	Nickel, hard	0.306
Brass, 30 Zn	0.350	Rubber	0.450–0.490
Cast steel	0.265	Silver	0.367
Chromium	0.210	Steel, mild	0.303
Copper	0.343	Steel, high carbon	0.295
Douglas fir	0.330	Steel, tool	0.287
Ductile iron	0.340–0.370	Steel, stainless (18-8)	0.305
Glass	0.245	Tin	0.342
Gray cast iron	0.210–0.270	Titanium	0.357
Iron, soft	0.293	Tungsten	0.280
Iron, cast	0.270	Vanadium	0.365
Inconel x	0.410	Wrought iron	0.278
Lead	0.431	Zinc	0.331
Magnesium	0.291		
Malleable cast iron	0.230		

TABLE 1-3
Mechanical properties of typical cast ferrous materials[a]

Material, class, specification		Ultimate strength						Torsional/ shear strength, τ_s		Yield strength, σ_{sy}		Endurance limit in reversed bending, σ_{sfb}		Brinell hardness, H_B	Modulation of elasticity						Elongation in 50 mm (2 in), %	Impact strength (Charpy)		Typical application
		Tension, σ_{sut}		Compression, σ_{suc}		Shear, τ_{su}									Tension, E		Compression, E		Shear, G					
		MPa	kpsi	MPa	kpsi	MPa	kpsi	MPa	kpsi	MPa	kpsi	MPa	kpsi		GPa	Mpsi	GPa	Mpsi	GPa	Mpsi		J	ft-lbf	
Gray cast iron[b]																								
ASTM class	SAE																							
20	110	152	22	572	83	220	32	179	26			69	10	156	66–97	9.6–14.0			27–39	3.9–5.6		75	55	Soft iron castings
25		179	26	669	97	255	37	220	32			79	11.5	174	79–102	11.5–14.8			32–41	4.6–6.0		75	55	Cylinder blocks and heads, housing
30	111	214	31	752	109	303	44	276	40			97	14	210	90–113	13.0–16.4			36–45	5.2–6.6				Flywheels, brake drums and clutch plates
35	120	252	36.5	855	124	338	49	334	48.5			110	16	212	10–119	14.5–17.2			40–48	5.8–6.9				Heavy-duty brake drums, clutch plates
40	121	293	42.5	965	140	393	57	393	57			128	18.5	235	110–138	16.0–20.0			44–54	6.4–7.8		95	70	Cam shafts, cylinder liners
50		362	52.5	1130	164	448	65	503	73			148	21.5	262	130–157	18.8–22.8			50–55	7.2–8.0		108	80	Special high-strength castings
60		431	62.5	1293	187.5	496	72	610	88.5			169	24.5	302	141–162	20.4–23.5			54–59	7.8–8.5		156	115	Special high-strength castings
Malleable cast iron:	Class or grade																							
Ferrite																								
ASTM A47-52, A338, ANSI G 48-1	32510	345	50	1434	208	324	47			220	32	193	28	156 max	172	25	172	25			10	22	16.5	General purpose at normal and elevated
FED QQ-1-66e	35018	365	53	1517	220	352	51			241	35	214	31	156 max	172	25	172	25			18	22	16.5	temperature, good machinability, excellent shock resistance.
ASTM A197		276	40							207	30			156 max							5			Pipe flanges, valve parts
Perlite and martensite:																								
ASTM A220	40010	414	60							276	40			149–197							10			General engineering
ANSI G48-2	45008	448	65							310	45			156–197							8			service at normal and
MIL-1-11444B	45006	448	65							310	45			156–207							6			elevated temperatures
	45010	448	65	1670	242	338	49			310	45	220	32	185	180	26	160	23.2			10	19	14	
	50005	483	70							345	50			179–229							5			
	50007	517	75	1670	242	517	75			345	50	255	37	204	183	26.5	160	23.2			7	19	14	
	60004	552	80							414	60			197–241							4			
	60003	552	80	1670	242	552	80			414	60	270	39	226	186	27	160	23.2			3	19	14	
	70003	586	85							483	70			217–269							3			
	80002	655	95	1670	242	689	100			552	80	276	40	241–285	186	27	160	27			2	19	14	
	90001	724	105							621	90			269–321							1			
Automotive	Grade																							
ASTMA602, SAE J158	M3210[c]	345	50							224	32			156 max							10			Steering gear housing, mounting brackets
	M4504[d]	448	65							310	45			163–217							4			Compressor crankshafts and hubs
	M5003[d]	517	75							345	50			187–241							3			Parts requiring selective hardening, as gears
	M5503[e]	517	75							379	55			187–241							3			For machinability and improved induction hardening
	M7002[e]	621	90							483	70			229–269							2			Connecting rods, universal joint yokes
	M8501[e]	724	105							586	85			269–302							1			Gears with high strength and good wear resistance

TABLE 1-3
Mechanical properties of typical cast ferrous materials[a] (*Cont.*)

			Ultimate strength						Torsional/ shear strength, τ_s		Yield strength, σ_{sy}		Endurance limit in reversed bending, σ_{sfb}		Brinell hardness, H_B	Modulation of elasticity						Elongation in 50 mm (2 in), %	Impact strength (Charpy)		Typical application
			Tension, σ_{sut}		Compression, σ_{suc}		Shear, τ_{su}									Tension, E		Compression, E		Shear, G					
Material, class, specification			MPa	kpsi	MPa	kpsi	MPa	kpsi	MPa	kpsi	MPa	kpsi	MPa	kpsi	H_B	GPa	Mpsi	GPa	Mpsi	GPa	Mpsi	(2 in), %	J	ft-lbf	Typical application
Nodular (ductile) cast iron																									
	Grade	UNS No.																							
ASTM A395-76 ASME SA 395	60-40-18	F32800	414	60							276	40			143–187							18			Valves and fittings for steam and chemical plant equipment
ASTM A476-70(d) SAE AMS5316	80-60-03	F34100	552	80							414	60			201 min							3			Paper-mill dryer rollers
ASTM A536-72 MIL-I-11466 B(MR)	60-40-18[h]	F32800	461	66.9	359	52.0	472	68.5			329	47.7	241	35	167–178	169	24.5	164	23.8	63–65.5[g]	9.1–9.5[g]	15			Pressure-containing parts such as valve and pump bodies
	65-45-12[h]	F33100	464	67.3	362	52.5	475	68.9			332	48.2			167	168	24.4	163	23.6	64–65[g]	9.3–9.4[g]	15			Machine components subjected to shock and fatigue loads
	80–55–06[h]	F33800	559	81.1	386	56.0	504	73.1			362	52.5	345	50	192	168	24.4	165	23.9	62–64[g]	9.0–9.3[g]	11.2			Crankshafts, gears and rollers
	100-70-03[h]	F34800	758	110	1515	220.0					500	72.5	379	55	257	162	23.5					6-10			High-strength gears and machine components
	120-90-02[h]	F36200	974	141.3	920	133.5	875	126.9			864	125.3	434	63	332	164	23.8	164	23.8	63.5–64[g]	9.2–9.3[g]	1.5			Pinions, gears, rollers and slides
SAE j 434C	D4018		414	60							276	40			170 max							18			Steering knuckles
	D4512		448	65							310	45			156–217							12			Disk brake calipers
	D5506		552	80							379	55			187–255							6			Crankshafts
	D7003		689	100							483	70			241–302							3			Gears
Alloy cast irons																									
Medium-silicon gray iron			170–310	24–45	620–1040	90–150									170–250								20–31	15–23	
High chromium gray iron			210–620	30–90	690	100									250–500								27–47	20–35	
High nickel gray iron			170–310	25–45	690–1100	100–160									130–250								80–200	60–150	
Ni-Cr-Si gray iron			140–310	20–45	480–690	70–100									110–210								110–200	80–150	
High-aluminum gray iron			235–620	34–90											180–350										
Medium-silicon ductile iron			415–690	60–100											140–300								7–155	5–115	
High-nickel ductile iron (20Ni)			380–415	55–60	1240–1380	180–200									140–200								16	12	
High-nickel ductile iron (23Ni)			400–450	58–65											130–170								38	28	
Durion			110	16											520	158	23						4	3	
Mechanite			241–380	35–55							193–241	28–35			190	83	12					10			

[a] *Source*: Compiled from *AMS Metals Handbook*, American Society for Metals, Metals Park, Ohio, 1988.
[b] Minimum values of σ_u in MPa (kpsi) are given by class number.
[c] Annealed.
[d] Air-quenched and tempered.
[e] Liquid-quenched and tempered.
[f] Heat-treated and average mechanical properties.
[g] Calculated from tensile modulus and Poisson's ratio in tension.

TABLE 1-4
Typical mechanical properties of gray cast iron

Grade	Tensile strength, σ_{st} MPa	kpsi	Compressive strength, σ_{sc} MPa	kpsi	Shear strength, τ_s MPa	kpsi	Fatigue limit, σ_{sf} MPa	kpsi	Modulus of elasticity, E, Tension GPa	Mpsi	Modulus of elasticity, E, Compression GPa	Mpsi	Modulus of rigidity, G GPa	Mpsi	Notched tensile strength, σ_{snt} MPa	kpsi	Elastic strain at failure, %	Total elastic strain at fracture, %	Brinell hardness H_B	Poisson's ratio, ν	Density, ρ kg/m^3	lb$_m$/ft^3	Coefficient of the thermal expansion, α, 20 to 200°C μm/mK	μin/in°F	Specific heat capacity at 20 to 200°C, c kJ/kg K	Btu/lb$_m$°F	Thermal conductivity at 100°C, K W/m^{2}K	Btu/ft^{2}h°F
FG 150	150	21.8	600	87.0	173	25.1	68[e]	9.9	100	14.5	100	14.5	40	5.8	120[a]	17.4	0.15	0.6–0.75[g]	130–180	0.26	7050	440.1	11.0	6.1	26.5	0.0640	52.5	9.25
	42[c]	6.0	84	12.2			68[f]	9.9							150[b]	21.8												
	98[d]	14.2	195	15.2																								
FG 200	200	29.0	720	104.4	230	33.4	90[e]	13.1	114	16.5	114	16.5	46	6.7	160[a]	23.2	0.17	0.48–0.67[g]	160–220	0.26	7100	443.3	11.0	6.1	0.375	0.0896	50.8	8.95
	56[c]	8.1	112	16.2			87[f]	12.6							200[b]	29.0												
	130[d]	18.8	260	37.7																								
FG 220	220	32.0	768	111.4	253	36.7	99[e]	14.4	120	17.4	120	17.4	48	7.0	176[a]	25.5	0.18	0.39–0.63[g]	180–220	0.26	7150	446.4	11.0	6.1	0.420	0.1003	50.1	8.82
	62[e]	9.0	123	17.8			94[f]	13.6							120[b]	32.0												
	143[d]	20.7	286	41.5																								
FG 260	260	37.7	864	125.3	299	43.4	117[e]	17.0	128	18.6	128	18.6	51	7.4	208[a]	30.2	0.20	0.57[g]	180–230	0.26	7200	449.5	11.0	6.1	0.460	0.1098	48.8	8.59
	73[c]	10.6	146	21.2			108[f]	15.7							260[b]	37.7												
	169[d]	24.5	338	49.0																								
FG 300	300	43.5	960	139.2	345	50.0	135[e]	19.6	135	19.6	135	19.6	54	7.8	240[a]	34.8	0.22	0.50[g]	180–230	0.26	7250	452.6	11.0	6.1	0.460	0.1098	47.4	8.35
	84[c]	12.2	168	24.4			127[f]	18.4							300[b]	43.5												
	195[d]	28.3	390	56.6																								
FG 350	350	50.8	1080	156.6	403	58.5	149[e]	21.6	140	20.3	140	20.3	56	8.1	280[a]	40.6	0.25	0.50[g]	207–241	0.26	7300	455.7	11.0	6.1	0.460	0.1089	45.7	8.05
	98[c]	14.2	196	28.4			129[f]	18.7							250[b]	50.8												
	228[d]	33.1	455	66.0																								
FG 400	400	58.0	1200	174.1	460	66.7	152[e]	2.0	145	21.0	145	21.0	58	8.4	320[a]	46.4	0.28	0.50[g]	207–270	0.26	7300	455.7	11.0	6.1	0.460	0.1089	44.0	7.75
	112[c]	16.2	224	32.5			127[f]	18.4							400[b]	58.0												
	260[d]	37.7	520	75.4																								

[a] Circumferential 45° notch-root radius 0.25 mm (0.04 in), notch depth 2.5 mm (0.4 in), root diameter 20 mm (0.8 in), notch depth 3.3 mm (0.132 in), notch diameter 7.6 mm (0.36 in).
[b] Circumferential notch radius 9.5 mm (0.38 in), notch depth 2.5 mm (0.4 in), notch diameter 20 mm (0.8 in).
[c] 0.01% proof stress.
[d] 0.1% proof stress.
[e] Unnotched 8.4 mm (0.336 in) diameter.
[f] V-notched [circumferential 45° V-notch with 0.25 mm (0.04 in) root radius, diameter at notch 8.4 mm (0.336 in), depth of notch 3.4 mm (0.135 in)].
[g] Values depend on the composition of iron.
[h] Poisson's ratio $\nu = 0.26$.

Note: The typical properties given in this table are the properties in a 30 mm (1.2 in) diameter separately cast test bar or in a casting section correctly represented by this size of test bar, where the tensile strength does not correspond to that given. Other properties may differ slightly from those given.
Source: IS (Indian Standards) 210, 1993.

TABLE 1-5
Mechanical properties of spheroidal or nodular graphite cast iron

Grade	Typical casting thickness		Density		Poisson's ratio, ν	Tensile strength, σ_{st} min		0.2% Proof stress, σ_{sy} min		Elongation[a] %, min	Brinell hardness, H_B	Impact values min ($23 \pm 5^\circ$C)		Predominant structural constituent
	mm	in	kg/m^3	lb$_m$/ft^3		MPa	kpsi	MPa	kpsi			J	ft-lbf	
						Measured on test pieces from separately cast test samples								
SG 900/2			7150	446.4	0.275	900	130.5	600	87.0	2	280–360			
SG 800/2			7200	449.5	0.275	800	116.0	480	69.6	2	245–335			Pearlite
SG 700/2			7200	449.5	0.275	700	101.5	420	61.0	2	225–305			Pearlite
SG 600/2			7170	447.6	0.275	600	87.0	370	53.7	2	190–270			Ferrite and pearlite
SG 500/7			7100	443.3	0.275	500	72.5	320	46.4	7	160–240			Ferrite and pearlite
SG 450/10			7100	443.3	0.275	450	65.3	310	45.0	10	160–210	9.0[b] (4.3)[c]	6.6 (3.2)	
SG 400/15			7100	443.3	0.275	400	58.0	250	36.3	15	130–180	17.0[b] (15.0)[c]	12.5 (11.0)	Ferrite
SG 400/18			7100	443.3	0.275	400	58.0	250	36.6	18	130–180	14.0[b] (11.0)[c]	10.3 (8.1)	
SG 350/22			7100	443.3	0.275	350	50.8	220	32.0	22	≤150	17.0[b] (14.0)[c]	12.5 (10.3)	Ferrite
						Measured on test pieces from cast-on test samples								
SG 700/2A	30–60	1.2–2.4				700	101.5	400	58.0	2	220–320			Pearlite
	61–200	2.44–8.0				650	94.3	380	55.1	1				
SG 600/3A	30–60	1.2–2.4				600	87.0	360	52.2	2	180–270			Ferrite + pearlite
	61–200	2.44–8.0				550	79.8	340	49.3	1				
SG 500/7A	30–60	1.2–2.4				450	65.3	300	43.5	7	170–240			Ferrite + pearlite
	61–200	2.44–8.0				420	61.0	290	42.0	5				
SG 400/15A	30–60	1.2–2.4				390	56.6	250	36.3	15	130–180			Ferrite
	61–200	2.44–8.0				370	53.7	240	34.8	12				
SG 400/18A	30–60	1.2–2.4				390	56.6	250	36.4	15	130–180	14[b] (11)[c]	10.3 (8.1)	Ferrite
	61–200	2.44–8.0				370	53.7	240	34.8	12		12[b] (9)[c]	8.8 (6.6)	
SG 350/22A	30–60	1.2–2.4				330	47.9	22-	31.9	18	≤150	17[b] (14)[c]	12.5 (10.3)	Ferrite
	61–200	2.44–8.0				320	46.4	210	30.6	15		15[b] (12)[c]	11.1 (8.8)	

Grade	Compression strength, σ_{sc}		Shear strength, σ_{sc}		Fatigue limit, σ_{sc}		Modulus of, Elasticity E		Modulus of rigidity, G				Thermal coefficient of linear expansion, α		Specific heat, c at 20° to 200°C		Thermal conductivity, at 100°C	
									GPa		MPsi							
	MPa	kpsi	MPa	kpsi	MPa	kpsi	GPa	Mpsi	Ten	Com	Ten	Com	µm/m K at 20° to 200°C	µin/in °F	kJ/kg K	Btu/lb$_m$°F	W/m^2 K	Btu/ft^{2}h°F
SG 900/2	550	79.8	810	117.5	317	46.0	67.1	9.73	169	169	24.5	24.5	11.0	6.1	0.461	0.1101	33.5	5.90
SG 800/2	362	52.5	720	107.4	304	44.1	68.6	9.95	169	169	24.5	24.5	11.0	6.1	0.461	0.1101	31.40	5.53
SG 700/2	318	46.1	630	91.4	280	40.6	86.6	9.95	169	169	24.5	24.5	11.0	6.1	0.461	0.1101	31.40	5.53
SG 600/2	286	41.5	540	78.3	248	35.0	67.9	9.85	169	169	24.5	24.5	11.0	6.1	0.461	0.1101	32.80	5.72
SG 500/7	272	39.5	45	65.3	224	32.5	65.9	9.56	169	169	24.5	24.5	11.0	6.1	0.461	0.1101	35.50	6.25
SG 450/10	253	36.7	405	58.7	210	30.5	65.9	9.56	174	174	25.2	25.2	11.0	6.1	0.461	0.1101	36.5	6.43
SG 400/15	216	31.3	360	52.2	195	28.3	65.9	9.56	176	176	25.2	25.2	11.0	6.1	0.461	0.1101	36.5	6.43
SG 400/18	216	31.3	360	52.2	195	28.3	65.9	9.86	176	176	25.2	25.2	11.0	6.1	0.461	0.1101	36.5	6.43
SG 350/22	181	31.3	315	45.7	180	26.1	65.9	9.56	169	169	24.5	24.5	11.0	6.1	0.461	0.1101	36.5	6.43

[a] Elongation is measured on an initial gauge length $L = 5d$ where d is the diameter of the gauge length of the test pieces. [b] Mean value from 3 tests on V-notch test pieces at ambient temperature. [c] Individual value.

Source: IS 1865, 1991.

TABLE 1-5A
Chemical composition[a] and mechanical properties[c] of spheroidal graphite austenitic cast iron

	Chemical composition[a], %							Density		Tensile strength, σ_{st} min		0.2% proof stress, σ_{sy} min				Impact values[d], min	
Grade	C_{max}	Si	Mn	Ni	Cr	P_{max}	Cu_{max}	kg/m^3	lb$_m$/ft^3	MPa	kpsi	MPa	kpsi	Elongation[b] %, min	Brinell hardness, H_B	J	ft-lb
ASG Ni 13 Mn 7	3.0	2.0–3.0	6.0–7.0	12.0–14.0	≤0.3	0.080	0.5	7300	455.7	390–460	56.6–66.7	210–260	30.5–37.7	15–25	130–170	15.0–27.5	11.1–20.3
ASG Ni 20 Cr 2	3.0	1.5–3.0	0.5–1.5	18.0–22.0	1.0–2.5	0.080	0.5	7400	462.0	370–470	53.7–68.2	210–250	30.5–36.3	7–20	140–200	13.5–27.5	10.0–20.3
ASG Ni 20 Cr 3	3.0	1.5–3.0	0.5–1.5	18.0–22.0	2.5–3.5	0.080	0.5	7400	462.0	390–490	56.6–71.1	210–260	30.5–37.7	7–15	150–255	12.0	8.9
ASG Ni 20 Si 5 Cr 2	3.0	4.5–5.5	0.5–1.5	18.0–22.0	1.0–2.5	0.080	0.5	7400	462.0	370–430	53.7–62.4	210–260	30.5–37.7	10–18	180–230	14.9	11.0
ASG Ni 22	3.0	1.0–3.0	1.5–2.5	21.0–24.0	<0.5	0.080	0.5	7400	462.0	370–440	53.7–63.8	170–250	24.7–36.3	20–40	130–170	20.0–33.0	14.8–24.3
ASG Ni 23 Mn 4	2.6	1.5–2.5	4.0–4.5	22.0–24.0	<0.2	0.080	0.5	7400	462.0	440–470	63.6–68.2	210–240	30.5–34.8	25–45	150–180	24.0	17.7
ASG Ni 30 Cr 1	2.6	1.5–3.0	0.5–1.5	28.0–32.0	1.0–1.5	0.080	0.5	7400	462.0	370–440	53.7–62.4	210–270	30.5–39.2	13–18	130–190	17.0	8.1
ASG Ni 30 Cr 3	2.6	1.5–3.0	0.5–1.5	28.0–32.0	2.5–3.5	0.080	0.5	7400	462.0	370–470	53.7–68.2	210–260	30.5–37.7	7–18	140–200	8.5	6.3
ASG Ni 30 Si 5 Cr 5	2.6	5.0–6.0	0.5–1.5	28.0–32.0	4.5–5.5	0.080	0.5	7400	462.0	390–490	56.6–70.5	240–310	34.8–45.0	1–4	110–250	3.9–5.9	2.9–4.4
ASG Ni 35	2.4	1.5–3.0	0.5–1.5	34.0–36.0	≤0.2	0.080	0.5	7600	474.5	370–410	53.7–59.5	210–240	30.5–34.8	20–40	130–180	20.5	15.1
ASG Ni 35 Cr 3	2.4	1.5–3.0	0.5–1.5	34.0–36.0	2.0–3.0	0.080	0.5	7600	474.5	370–440	53.7–63.8	210–290	30.5–42.1	7–10	140–190	7.0	5.2

	Modulus of elasticity E		Thermal coefficient of linear expansion, α		Thermal conductivity, K		
Grade	GPa	Mpsi	µm/m K at 20 to 200°C	µin/in °F	W/m^2 K	Btu/ft^{2}h°F	Properties and applications
ASG Ni 13 Mn 7	140–150	20.3–21.8	18.2	10.1	12.6	2.22	Non-magnetic. Hence used as pressure covers for turbine generator sets, housing for insulators, flanges and switch gears.
ASG Ni 20 Cr 2	112–130	16.2–18.9	18.7	10.4	12.6	2.22	Corrosion and heat resistance. Used in pumps, valves, compressor exhaust gas manifolds, turbo-supercharger housings and bushings.
ASG Ni 20 Cr 3	112–133	16.2–19.3	18.7	10.4	12.6	2.22	Good resistance to corrosion. Used in valves, pump components and components subject to high pressure.
ASG Ni 20 Si 5 Cr 2	112–133	16.2–19.3	18.0	10.0	12.6	2.22	High value of linear expansion and non-magnetic. Used for pumps, valves, compressor and exhaust gas manifold and turbocharge housings.
ASG Ni 22	85–112	12.3–16.2	18.4	10.2	12.6	2.22	High impact properties up to −196°C and non-magnetic. Used in castings for refrigerators, etc.
ASG Ni 23 Mn 4	120–140	17.4–20.3	14.7	8.2	12.6	2.22	Good bearing properties. Used in exhaust manifolds and pumps, valves and turbocharger gas housing.
ASG Ni 30 Cr 1	112–130	16.2–18.9	12.6	7.0	12.6	2.22	Used in boiler pumps, valves, filter parts and exhaust gas manifolds.
ASG Ni 30 Cr 3	92–105	13.3–15.2	12.6	7.0	12.6	2.22	Used in pump components, valves, etc.
ASG Ni 30 Si 5 Cr 5	91	13.2	14.4	8.0	12.6	2.22	Power lower linear coefficient of expansion. Used in machine tool parts, scientific instruments, glass molds, and parts requiring dimensional stability.
ASG Ni 35	112–140	16.2–20.3	5	2.8	12.6	2.22	Possess lower linear thermal expansion. Used in gas turbine housings and glass molds.
ASG Ni 35 Cr 3	112–123	16.2–17.8	5	2.8	12.6	2.22	

[a] Unless otherwise specified, other elements may be present at the discretion of the manufacturer, provided they do not alter the micro-structure substantially, or affect the property adversely.
[b] Elongation is measured on an initial gauge length $L = 5d$ where d is the diameter of the gauge length of the test pieces. [c] Measured on test pieces machined from separately cast test samples.
[d] Mean value from 3 tests on V-notch test pieces at ambient temperature.
Source: IS 2749, 1974.

TABLE 1-5B
Chemical composition[a] and mechanical properties[b] of flake graphite austenitic cast iron

Grade	Chemical composition, %						Density		Tensile strength, σ_{st} min		Elongation %, min	Brinell hardness, H_B	Ultimate compressive strength, σ_{sut}		Modulus of elasticity, E	
	C	Si	Mn	Ni	Cr	Cu	kg/m^3	lb_m/ft^3	MPa	kpsi			MPa	kpsi	GPa	Mpsi
AFG Ni 13 Mn 7	≤3.0	1.5–3.0	6.0–7.0	12.0–14.0	0.2	≤0.5	7300	455.7	140–220	20.3–32.0	–	120–150	630–840	91.4–121.8	70–90	10.2–13.1
AFG Ni 15 Cu 6 Cr 2	≤3.0	1.0–2.8	0.5–1.5	13.5–17.5	1.0–2.5	5.5–7.5	7300	455.7	170–210	24.7–30.5	2	140–200	700–840	101.5–121.8	85–105	12.3–15.2
AFG Ni 15 Cu 6 Cr 3	≤3.0	1.0–2.8	0.5–1.5	13.5–17.5	2.5–3.5	5.5–7.5	7300	455.7	190–240	27.6–34.8	1–2	150–250	860–1100	124.7–159.5	98–113	14.2–16.4
AFG Ni 20 Cr 2	≤3.0	1.0–2.8	0.5–1.5	18.0–22.0	1.0–2.5	≤0.5	7300	455.7	170–210	24.7–30.5	2–3	120–215	700–840	101.5–121.8	85–105	12.3–15.2
AFG Ni 20 Cr 3	≤3.0	1.0–2.8	0.5–1.5	18.0–22.0	2.5–3.5	≤0.5	7300	455.7	190–240	27.6–34.8	1–2	160–250	860–1100	124.7–159.5	98–113	14.2–16.4
AFG Ni 20 Si 5 Cr 3	≤2.5	4.5–5.5	0.5–1.5	18.0–22.0	1.5–4.5	≤0.5	7300	455.7	190–280	27.6–40.6	2–3	140–250	860–1100	124.7–159.5	110	16.0
AFG Ni 30 Cr 3	≤2.5	1.0–2.0	0.5–1.5	28.0–32.0	2.5–3.5	≤0.5	7300	455.7	190–240	27.6–34.8	1–3	120–215	700–910	101.5–132.0	98–113	14.2–15.2
AFG Ni 30 Si 5 Cr 5	≤2.5	5.0–6.0	0.5–1.5	29.0–32.0	4.5–5.5	≤0.5	7300	455.7	170–240	27.4–34.8	–	150–210	560	81.2	105	15.2
AFG Ni 35	≤2.4	1.0–2.0	0.5–1.5	34.0–36.0	≤0.2	≤0.5	7300	455.7	120–180	17.4–26.1	1–3	120–140	560–700	81.2–101.5	74	10.7

Grade	Thermal coefficient of linear expansion, α		Specific hear, c		Thermal conductivity, K		Properties and applications
	μm/m K at 20 to 200°C	μin/in °F	J/kg K	Btu/lb_m°F	W/m^2 K	Btu/ft^2h°F	
AFG Ni 13 Mn 7	17.7	9.3	460–500	0.11–0.12	37.7–41.9	6.64–7.38	Non-magnetic. Used in pressure covers for turbine generator sets, housing for switch gears and terminals, and ducts.
AFG Ni 15 Cu 6 Cr 2	18.7	10.4	460–500	0.11–0.12	37.7–41.9	6.64–7.38	Resistance to corrosion, erosion, and heat. Good bearing properties. Used for pumps, valves, piston ring covers for
AFG Ni 15 Cu 6 Cr 3	18.7	10.4	460–500	0.11–0.12	37.7–41.9	6.64–7.38	pistons, furnace components, bushings.
AFG Ni 20 Cr 2	18.7	10.4	460–500	0.11–0.12	37.7–41.9	6.64–7.38	Possess high coefficient of thermal expansion, resistance to corrosion and erosion. Used for pumps handling alkalis.
AFG Ni 20 Cr 3	18.7	10.4	460–500	0.11–0.12	37.7–41.9	6.64–7.38	Used in soap, food and plastic industries.
AFG Ni 20 Si 5 Cr 3	18.0	10.0	460–500	0.11–0.12	37.7–41.9	6.64–7.38	Resistance to erosion, corrosion, heat. Used in high temperature application. Not suitable between 500 and 600°C.
							Resistance to thermal shock and heat, corrosion at high temperature. Used in pumps, pressure vessels, valves, filters,
							exhaust gas manifolds, turbine housings.
AFG Ni 30 Cr 3	12.4	6.9	460–500	0.11–0.12	37.7–41.9	6.64–7.38	Resistance to erosion, corrosion, and heat. Possess average thermal expansion. Used in components for industrial
AFG Ni 30 Si 5 Cr 5	14.6	8.1	460–500	0.11–0.12	37.7–41.9	6.64–7.38	furnaces, valves, and pump components. Possess low thermal expansion and resistant to thermal shock. Used for
AFG Ni 35	5.0	2.8	460–500	0.11–0.12	37.7–41.9	6.64–7.38	scientific instruments, glass molds and in such other parts where dimensional stability is required

[a] Unless otherwise specified other elements may be present at the discretion of the manufacturer, provided they do not alter the microstructure substantially, or affect the properties adversely.
[b] Measured on test pieces machined from separately cast test pieces/samples.
Source: IS 2749, 1974.

TABLE 1-6
Carbon steels with specified chemical composition and related mechanical properties

Designation				Tensile strength, σ_{st}		Elongation, % (gauge length $5.56\sqrt{a^*}$ round test piece)	Izod impact value, min (if specified)	
New	Old	% C	% Mn	MPa	kpsi		J	ft-lbf
7 C 4	(C 07)	0.12 max	0.50 max	320–400	46.5–58.0	27		
10 C 4	(C 10†)	0.15 max	0.30–0.60	340–420	49.4–70.0	26	55	40.6
14 C 6	(C 14†)	0.10–0.18	0.40–0.70	370–450	53.6–65.0	26	55	40.6
15 C 4	(C 15)	0.20 max	0.30–0.60	370–490	53.6–71.0	25		
15 C 8	(C 15 Mn $\underline{75}$)	0.10–0.20	0.60–0.90	420–500	61.0–72.5	25		
20 C 8	(C 20)	0.15–0.25	0.60–0.90	440–520	63.5–75.4	24		
25 C 4	(C 25)	0.20–0.30	0.30–0.60	440–540	63.5–78.3	23		
25 C 8	(C 25 Mn $\underline{75}$ +)	0.20–0.30	0.60–0.90	470–570	68.2–82.7	22		
30 C 8	(C 30 +)	0.25–0.35	0.60–0.90	500–600	72.5–87.0	21	55	40.6
35 C 4	(C 35)	0.30–0.40	0.30–0.60	520–620	75.4–90.0	20		
35 C 8	(C 35 Mn $\underline{75}$ +)	0.30–0.40	0.60–0.90	550–650	79.8–94.3	20	55	40.6
40 C 8	(C 40 +)	0.35–0.45	0.60–0.90	580–680	84.1–98.7	18	41.35	30.5
45 C 8	(C 45 +)	0.40–0.50	0.60–0.90	630–710	91.4–103.0	15	41.35	30.5
50 C 4	(C 50 +)	0.45–0.55	0.60–0.90	660–780	95.7–113.1	13		
50 C 12	(C 50 Mn 1)	0.45–0.55	1.10–1.40	720 min	104.4 min	11		
55 C 8	(C 55 Mn $\underline{75}$ +)	0.50–0.60	0.60–0.90	720 min	104.4 min	13		
60 C 4	(C 60)	0.55–0.65	0.50–0.80	750 min	108.8 min	11		
65 C 6	(C 65)	0.60–0.70	0.50–0.80	750 min	108.8 min	10		

Notes: a^*, area of cross section; † steel for hardening; + steel for hardening and tempering; Mn $\underline{75}$ = average content of Mn is 0.75%.
Source: IS 1570, 1979.

TABLE 1-7
Carbon and carbon - manganese free - cutting steels with specified chemical composition and related mechanical properties

Designation							Tensile strength, σ_{st}		Minimum elongation, % (gauge length 5.65 $\sqrt{a^{**}}$)	Izod impact value, min (if specified)		Limiting ruling section, mm (in)
New	Old	% C	% Si	% Mn	% S	% P (max)	MPa	kpsi		J	ft-lbf	
10 C 8 S 10	(10 S 11)	0.15 max	0.05–0.30	0.60–0.90	0.08–0.13	0.060	370–490*	53.7–71.0	24*	55	40.6	30 (1.2)
14 C 14 S 14	(14 Mn 1 S 14)	0.10–0.18	0.05–0.30	1.20–1.50	0.10–0.18	0.060	440–540*	63.8–78.3	22*			30 (1.2)
25 C 12 S 14	(25 Mn 1 S 14)	0.20–0.30	0.25 max	1.00–1.50	0.10–0.18	0.060	500–600*	72.5–87.0	20*			
40 C 10 S 18	(40 S 18)	0.35–0.45	0.25 max	0.80–1.20	0.14–0.22	0.060	550–650*	79.8–94.0	17*	41	30.2	60 (2.4)
11 C 10 S 25	(11 S 25)	0.08–0.15	0.10 max	0.80–1.20	0.20–0.30	0.060	370–490*	53.7–71.0	22*			
40 C 15 S 12	(40 Mn 2 S 12)	0.35–0.45	0.25 max	1.30–1.70	0.08–0.15	0.060	600–700*	87.0–101.5	15*	48	35.4	100 (4.0)

Notes: a^{**}, area of cross section; *, steel for case hardening. Minimum values of yield stress may be required in certain specifications, and in such case a minimum yield stress of 55 percent of minimum tensile strength should be satisfactory.
Source: IS 1570, 1979.

TABLE 1-8
Mechanical properties of selected carbon and alloy steels

AISI[a] no.	UNS no.	Treatment	Austenitizing temperature °C	°F	Tensile strength, σ_{st} MPa	kpsi	Yield strength, σ_{sy} MPa	kpsi	Elongation in 50 mm (2 in), %	Reduction in area, %	Brinell hardness, H_B	Izod impact strength J	ft-lbf
1010	G10100	Hot-rolled			320	47	180	26	28	50	95		
		Cold-drawn			370	53	300	44	20	40	105		
1015	G10150	As rolled	–	–	420.6	61.0	313.7	45.5	39.0	61.0	126	110.5	81.5
		Normalized	925	1700	424.0	61.5	324.1	47.0	37.0	69.6	121	115.5	85.2
		Annealed	870	1600	386.1	56.0	284.4	41.3	37.0	69.7	111	115.0	84.8
1020	G10200	As-rolled			448.2	65.0	330.9	48.0	36.0	59.0	143	86.8	64.0
		Normalized	870	1600	441.3	64.0	346.5	50.3	35.8	67.9	131	117.7	86.8
		Annealed	870	1600	394.7	57.3	294.8	42.3	36.5	66.0	111	123.4	91.0
1030	G10300	As-rolled			551.6	80.0	344.7	50.0	32.0	57.0	179	74.6	55.0
		Normalized	925	1700	520.0	75.5	344.7	50.0	32.0	60.8	149	93.6	69.0
		Annealed	845	1550	463.7	67.3	341.3	49.5	31.2	57.9	126	69.4	51.2
1040	G10400	As-rolled			620.5	90.0	413.7	60.0	25.0	50.0	201	48.8	36.0
		Normalized	900	1650	589.5	85.5	374.0	54.3	28.0	54.9	170	65.1	48.0
		Annealed	790	1450	518.8	75.3	353.4	51.3	30.2	57.2	149	44.3	32.7
1050	G10500	As-rolled			723.9	105.0	413.7	60.0	20.0	40.0	229	31.2	23.0
		Normalized	900	1650	748.1	108.5	427.5	62.0	20.0	39.4	217	27.1	20.0
		Annealed	790	1450	636.0	92.3	365.4	53.0	23.7	39.9	187	16.9	12.5
1060	G10600	As-rolled			813.7	118.0	482.6	70.0	17.0	34.0	241	17.6	13.0
		Normalized	900	1650	775.7	112.5	420.6	61.0	18.0	37.2	229	13.2	9.7
		Annealed	790	1450	625.7	90.8	372.3	54.0	22.5	38.2	179	11.3	8.3
1095	G10950	As-rolled			965.3	140.0	572.3	83.0	9.0	18.0	293	4.1	3.0
		Normalized	900	1650	1013.5	147.0	499.9	72.5	9.5	13.5	293	5.4	4.0
		Annealed	790	1450	656.7	95.3	379.2	55.0	13.0	20.6	192	2.7	2.0
1117	G11170	As-rolled			486.8	70.6	305.4	44.3	33.0	63.0	143	81.3	60.0
		Normalized	900	1650	467.1	67.8	303.4	44.0	33.5	63.8	137	85.1	62.8
		Annealed	825	1575	429.5	62.3	279.2	40.5	32.8	58.0	121	93.6	69.0
1144	G11440	As-rolled			703.3	102.0	420.6	61.0	21.0	41.0	212	52.9	39.0
		Normalized	900	1650	667.4	96.8	399.9	58.0	21.0	40.4	197	43.4	32.0
		Annealed	790	1450	584.7	84.8	346.8	50.3	24.8	41.3	167	65.1	48.0
1340	G13400	Normalized	870	1600	836.3	121.3	558.5	81.0	22.0	62.9	248	92.5	68.2
		Annealed	800	1475	703.3	102.0	436.4	63.3	25.5	57.3	207	70.5	52.0

TABLE 1-8
Mechanical properties of selected carbon and alloy steels (*Cont.*)

AISI[a] no.	UNS no.	Treatment	Austenitizing temperature °C	°F	Tensile strength, σ_{st} MPa	kpsi	Yield strength, σ_{sy} MPa	kpsi	Elongation in 50 mm (2 in), %	Reduction in area, %	Brinell hardness, H_B	Izod impact strength J	ft-lbf
3140	G31400	Normalized	870	1600	891.5	129.3	599.8	87.0	19.7	57.3	262	53.6	39.5
		Annealed	815	1500	689.5	100.0	422.6	61.3	24.5	50.8	197	46.4	34.2
4130	G41300	Normalized	870	1600	668.8	97.0	436.4	63.3	25.2	59.5	197	86.4	63.7
		Annealed	865	1585	560.5	81.3	360.6	52.3	28.2	55.6	156	61.7	45.5
4150	G41500	Normalized	870	1600	1154.9	167.5	734.3	106.5	11.7	30.8	321	11.5	8.5
		Annealed	815	1500	729.5	105.8	379.2	55.0	20.2	40.2	197	24.7	18.2
4320	G43200	Normalized	895	1640	792.9	115.0	464.0	67.1	20.8	50.7	235	72.9	53.8
		Annealed	850	1560	579.2	84.0	609.5	61.6	29.0	58.4	163	109.8	81.0
4340	G43400	Normalized	870	1600	1279.0	185.5	861.8	125.0	12.2	36.3	363	15.9	11.7
		Annealed	810	1490	744.6	108.0	472.3	68.5	22.0	49.9	217	51.1	37.7
4620	G46200	Normalized	900	1650	574.3	83.3	366.1	53.1	29.0	66.7	174	132.9	98.0
		Annealed	855	1575	512.3	74.3	372.3	54.0	31.3	60.3	149	93.6	69.0
4820	G48200	Normalized	860	1580	750.0	109.5	484.7	70.3	24.0	59.2	229	109.8	81.0
		Annealed	815	1500	681.2	98.8	464.0	67.3	22.3	58.8	197	92.9	68.5
5150	G51500	Normalized	870	1600	870.8	126.3	529.5	76.8	20.7	58.7	255	31.5	23.2
		Annealed	825	1520	675.7	98.0	357.1	51.8	22.0	43.7	197	25.1	18.5
6150	G61500	Normalized	870	1600	939.8	136.3	615.7	89.3	21.8	61.0	269	35.5	26.2
		Annealed	815	1500	667.4	96.8	412.3	59.8	23.0	48.4	197	27.4	20.2
8630	G86300	Normalized	870	1600	650.2	94.3	429.5	62.3	23.5	53.5	187	94.6	69.8
		Annealed	845	1550	564.0	81.8	372.3	54.0	29.0	58.9	156	95.2	70.2
8740	G87400	Normalized	870	1600	929.4	134.8	606.7	88.0	16.0	47.9	269	17.6	13.0
		Annealed	815	1500	695.0	100.8	415.8	60.3	22.2	46.4	201	40.0	29.5
9255	G92550	Normalized	900	1650	932.9	135.3	579.2	84.0	19.7	43.4	269	13.6	10.0
		Annealed	845	1550	774.3	112.3	486.1	70.5	21.7	41.1	229	8.8	6.5
9310	G93100	Normalized	890	1630	906.7	131.5	570.9	82.8	18.8	58.1	269	119.3	88.0
		Annealed	845	1550	820.5	119.0	439.9	63.8	17.3	42.1	241	78.6	58.0

[a] All grades are fine-grained except for those 1100 series, which are coarse-grained. Heat-treated specimens were oil-quenched unless otherwise indicated.
Values tabulated were averaged and obtained from specimen 12.75 mm (0.505 in) in diameter which were machined from 25 mm (1 in); rounded gauge lengths were 50 mm (2 in).
Source: *ASM Metals Handbook,* American Society for Metals. Metals Park, Ohio. 1988

TABLE 1-9
Mechanical properties of standard steels

Designation		Tensile strength, σ_{st}		Yield stress, σ_{sy}		Elongation in 50 mm (gauge length 5.65 $\sqrt{a^*}$)
New	Old	MPa	kpsi	MPa	kpsi	
Fe 290	(St 30)	290	42.0	170	24.7	27
Fe E 220	–	290	42.0	220	32.0	27
Fe 310	(St 32)	310	45.0	180	26.1	26
Fe E 230	–	310	45.0	230	33.4	26
Fe 330	(St 34)	330	47.9	200	29.0	26
Fe F 250	–	330	47.9	250	36.3	26
Fe 360	(St 37)	360	52.2	220	32.0	25
Fe F 270	–	360	52.2	270	39.2	25
Fe 410	(St 42)	410	59.5	250	36.3	23
Fe E 310	–	410	59.5	310	50.0	23
Fe 490	(St 50)	490	71.1	290	42.0	21
Fe E 370	–	490	71.1	370	53.7	21
Fe 540	(St 55)	540	78.3	320	46.4	20
Fe E 400	–	540	78.3	400	58.0	20
Fe 620	(St 63)	620	90.0	380	55.1	15
Fe E 460	–	620	90.0	460	66.7	15
Fe 690	(St 70)	690	100.0	410	59.5	12
Fe E 520	–	690	100.0	520	75.4	12
Fe 770	(St 78)	770	111.7	460	66.7	10
Fe E 580	–	770	111.7	580	84.1	10
Fe 870	(St 88)	870	126.2	520	75.4	8
Fe E 650	–	870	126.2	650	94.3	8

Note: a^* area of cross-section of test specimen.
Source: IS 1570, 1978.

TABLE 1-10
Chemical composition and mechanical properties of carbon steel castings for surface hardening

	Chemical composition (in ladle analysis) max, %									
Designation	C	Si	Mn	S	P	Cr	Ni	Mo	Cu	Residual elements
Gr 1	0.4-0.5	0.60	1.0	0.05	0.05	0.25	0.40	0.15	0.30	0.80
Gr 2	0.5-0.6	0.60	1.0	0.05	0.05	0.25	0.40	0.15	0.30	0.80

	Tensile strength, σ_{st}		Yield strength, σ_{sy}		Elongation, % min (gauge length 5.65 $\sqrt{a^*}$)	Brinell hardness H_B
Designation	Mpa	kpsi	Mpa	kpsi		
Gr 1	620	90.0	320	46.4	12	460
Gr 2	700	101.5	370	53.7	8	535

Notes: a^* area of cross section of test specimen. All castings shall be free from distortion and harmful defects. They shall be well-dressed, fettled, and machinable. Unless agreed upon by the purchaser and the manufacturer, castings shall be supplied in the annealed, or nomalized and tempered condition.
Source: IS 2707, 1973.

TABLE 1-11
Chemical composition of alloy steel forgings for general industrial use

Designation									
New	Old	% C	% Si	% Mn	% Ni	% Cr	% Mo	% V	% Al
20 C 15	20 Mn 2	0.06–0.24	0.10–0.35	1.30–1.70					
15 Cr 3	15 Cr 65	0.12–0.18	0.10–0.35	0.40–0.60		0.50–0.80			
16 Mn 5 Cr 4	17 Mn 1 Cr 95	0.14–0.19	0.10–0.35	1.00–1.30		0.80–1.10			
20 Mn 5 Cr 5	20 Mn Cr 1	0.18–0.22	0.10–0.35	1.00–1.40		1.00–1.30			
21 Cr 4 Mo 2	21 Cr 1 Mo 28	0.26 max	0.10–0.35	0.50–0.80		0.90–1.20	0.15–0.30		
07 Cr 4 Mo 6	07 Cr 90 Mo 55	0.12 max	0.15–0.60	0.40–0.70	0.30 max	0.70–1.10	0.45–0.65		
10 Cr 9 Mo 10	10 Cr 2 Mo 1	0.15 max	0.50 max	0.40–0.70	0.30 max	2.00–2.50	0.90–1.10		
13 Ni 13 Cr 3	13 Ni 3 Cr 80	0.10–0.15	0.10–0.35	0.40–0.70	3.00–3.50	0.60–1.00			
15 Ni 16 Cr 5	15 Ni 4 Cr 1	0.12–0.18	0.10–0.35	0.40–0.70	3.80–4.30	1.00–1.40			
15 Ni 5 Cr 4 Mo 1	15 Ni Cr 1 Mo 12	0.12–0.18	0.10–0.35	0.60–1.00	1.00–1.50	0.75–1.25	0.80–0.15		
15 Ni 7 Cr 4 Mo 2	15 Ni Cr 1 Mo 15	0.12–0.18	0.10–0.35	0.60–1.00	1.50–2.00	0.75–1.25	0.10–0.20		
16 Ni 8 Cr 6 Mo 2	16 Ni Cr 2 Mo 20	0.12–0.20	0.10–0.35	0.40–0.70	1.80–2.20	1.40–1.70	0.15–0.25		
36 S 17	37 Si 2 Mn 90	0.33–0.40	1.50–2.00	0.80–1.00					
37 C 15	37 Mn 2	0.32–0.42	0.10–0.35	1.30–1.70					
35 Mn 6 Mo 3	35 Mn 2 Mo 28	0.30–0.40	0.10–0.35	1.30–1.80			0.20–0.35		
40 Cr 4	40 Cr 1	0.35–0.45	0.10–0.35	1.60–0.90		0.90–1.70			
40 Cr 4 Mo 3	40 Cr 1 Mo 28	0.35–0.45	0.10–0.35	0.50–0.80		0.90–1.20	0.20–0.35		
35 Ni 5 Cr 2	35 Ni 1 Cr 60	0.30–0.40	0.10–0.35	0.60–0.90	1.00–1.50	0.45–0.75			
40 Ni 6 Cr 4 Mo 3	40 Ni 2 Cr 1 Mo 28	0.35–0.45	0.10–0.35	0.40–0.70	1.25–1.75	0.90–1.30	0.20–0.35		
40 Ni 10 Cr 3 Mo 6	40 Ni 3 Cr 65 Mo 55	0.36–0.44	0.10–0.35	0.40–0.70	2.25–2.75	0.50–0.80	0.40–0.70		
25 Cr 13 Mo 6	25 Cr 3 Mo 55	0.20–0.30	0.10–0.35	0.40–0.70	0.30 max	2.90–3.40	0.45–0.65		
55 Si 7	55 Si 2 Mn 90	0.50–0.60	1.50–2.00	0.80–1.00					
50 Cr 4 V 2	50 Cr 1 V 23	0.45–0.55	0.10–0.35	0.50–0.80		0.90–1.20		0.15–0.30	
20 Ni Cr MO 2		0.18–0.23	0.20–0.35	0.70–0.90	0.40–0.70	0.40–0.60	0.15–0.25		
37 Mn 5 Si 5		0.33–0.41	1.10–1.40	1.10–1.40					

Notes: (1) Sulfur and phosphorus can be ordered as per following limits: (i) S and P – 0.30 max; (ii) S – 0.02–0.035 and P – 0.035 max. (2) When the steel is Al killed, total Al contents shall be between 0.02–0.05 percent.
Source: IS 4367, 1991.

TABLE 1-12
Mechanical properties of alloy steel forgings for general industrial use

Designation	Condition	Tensile strength,[b] σ_{st}		Yield strength,[b] σ_{sy}		Brinell hardness in soft annealed condition, max, H_B	Elongation,[b] %, min (gauge length $5.65\sqrt{a^*}$)[a]	Izod impact[b] value		Brinell[b] hardness number H_B	Limiting ruling section	
		MPa	kpsi	MPa	kpsi			J	ft-lbf		mm	in
20 C 15	H and T	600–750	87.0–108.8	400	58.0	200	18	50	36.9	178–221	63	2.52
		700–850	101.5–123.3	460	66.7		16	50	36.9	208–252	63	1.20
30 C 15	H and T	600–750	87.0–108.8	440	63.8	220	18	50	36.9	178–221	150	6.00
		700–850	101.5–123.3	540	78.3		18	48	35.4	208–252	100	4.00
		800–950	116.0–137.8	600	87.0		16	48	35.4	235–280	63	2.52
15 Cr 3	R, Q and S.R	600 min	87.0 min			170	13	48	35.4		30	1.20
16 Mn 5 Cr 4	R, Q and S.R	800 min	116.0 min			207	10	35	25.8		30	1.20
20 Mn 5 Cr 5	R, Q and S.R	1000 min	145.0 min			217	8	38	28.0		30	1.20
21 Cr 4 Mo 2	H and T	650–800	94.3–116.0	420	61.0	210	16	60	44.3	190–235	150	6.00
		700–850	101.5–123.3	460	66.7		15	55	40.6	208–252	100	4.00
		800–950	116.0–137.8	580	84.1		14	50	36.9	235–280	40	1.60
7 Cr 4 Mo 6	N and T	380–550	55.1–79.8	225	32.6	170	19	60	44.3		40	1.60
10 Cr 9 Mo 10	N and T	410–590	59.5–85.6	245	35.5	187	18	55	40.6		50	2.00
		520–680	75.4–98.6	310	45.0		18	50	36.9			
13 Ni 13 Cr 3	R, Q and S.R	850 min	123.3 min			229	12	48	35.4		60	2.4
15 Ni 16 Cr 5	R, Q and S.R	1350 min	195.8 min			241	9	35	25.8		30	1.20
15 Ni 5 Cr 4 Mo 1	R, Q and S.R	1000 min	145.0 min			217	9	41	30.2		30	1.20
15 Ni 7 Cr 4 Mo 2	R, Q and S.R	1100 min	159.5 min			217	9	35	25.8		30	1.20
16 Ni 8 Cr 6 Mo 2	R, Q and S.R	1350 min	195.8 min			229	9	35	25.8		30	1.20
20 Ni Cr Mo 2	R, Q and S.R	900 min	130.5 min			213	11	41	30.2			
36 Si 7	H and T	800–950	116.0–137.8			217				235–280	100	4.00
37 Mn 5 Si 5	H and T	780–930	113.1–134.9	590	85.6	217	14					
55 Si 7	H and T	1300–1500	188.6–217.6			245				380–440	100	4.00
35 Mn 6 Mo 3	H and T	700–850	101.5–123.3	540	78.3	220	18	55	40.6	208–252	150	6.00
		900–1050	130.5–152.3	700	101.5		15	50	36.9	268–311	63	2.52
		1000–1150	145.0–166.8	800	116.0		13	45	33.2	295–341	30	1.20
40 Cr 4	H and T	700–850	101.5–123.3	540	78.3	220	18	55	40.6	208–252	100	4.00
		900–1050	130.5–152.3	700	101.5		15	50	36.9	266–311	30	1.20
40 Cr 4 Mo 3	H and T	700–850	101.5–123.3	540	78.3	220	18	55	40.6	208–252	150	6.00
		900–1050	130.5–152.3	700	101.5		15	50	36.9	266–311	63	2.52
		1000–1150	145.0–166.8	800	116.0		13	45	33.2	295–341	30	1.20
35 Ni 5 Cr 2	H and T	700–850	101.5–123.3	540	78.3	220	18	55	40.6	208–252	150	6.00
		900–1050	130.5–152.3	700	101.5		15	50	36.9	266–311	63	2.52

TABLE 1–12
Mechanical properties of alloy steel forgings for general industrial use (*Cont.*)

Designation	Condition	Tensile strength,[b] σ_{st} MPa	Tensile strength,[b] σ_{st} kpsi	Yield strength,[b] σ_{sy} MPa	Yield strength,[b] σ_{sy} kpsi	Brinell hardness in soft annealed condition, max, H_B	Elongation,[b] %, min (gauge length $5.65\sqrt{a^*}$)[a]	Izod impact[b] value J	Izod impact[b] value ft–lbf	Brinell[b] hardness number H_B	Limiting ruling section mm	Limiting ruling section in
25 Cr 13 Mo 6		900–1050	130.5–152.3	700	101.5	230	15	55	40.6	266–311	150	6.00
		1100–1250	159.5–181.3	880	127.6		12	41	30.2	325–370	100	4.00
40 Ni 6 Cr 4 Mo 3	H and T	900–1050	130.5–152.3	700	101.5	230	55	55	40.6	266–311	150	6.00
		1100–1250	159.5–181.3	880	127.6		11	41	30.2	325–370	63	2.52
		1200–1350	174.0–195.8	1000	145.0		10	30	22.1	355–399	30	1.20
40 Ni 10 Cr 3 Mo 6	H and T	1000–1150	145.0–166.8	800	116.0	250	12	48	35.4	295–341	150	6.00
		1200–1350	174.0–195.8	1000	145.0		10	35	25.8	355–399	150	6.00
		1550 min	224.8 min	1300	188.5		8	15	11.1	450 min	100	4.00
50 Cr 4 V 2	H and T	900–1100	130.5–159.5	700	101.5	240	12	45	33.2	266–325	100	4.00
		1000–1200	145.0–174.0	800	116.0		10	45	33.2	295–355	40	1.60

[a] a^*, area of cross section.
[b] Mechanical properties in heat-treated conditions.
Notes: H and T – hardened and tempered; N and T – normalized and tempered; R,Q and S.R – refined quenched and stress-relieved. All properties for guidance only. Other values may be mutually agreed on between the consumers and suppliers.
Source: IS 4367, 1991.

TABLE 1–13
Chemical composition and mechanical properties of alloy steels**

Designation	Percent C	Si	Mn	Ni	Cr	Mo	V/Al	Tensile strength, σ_{st} MPa	kpsi	0.2% proof stress, min, σ_{sy} MPa	kpsi	Minimum elongation (gauge length $= 5.65\sqrt{a^*})^a$, %	Minimum Izod impact value J	ft-lbf	Brinell[#] hardness H_B	Limiting ruling section, mm (in)[+]
20 C 15 (20 Mn 2)[##]	0.16–	0.10–	1.30–					590–740	85.6–107.3	390	56.6	18	48	35.4	170–217	63 (2.5)[+]
	0.24	0.35	1.70					690–840	100.0–121.8	450	65.3	16	48	35.4	201–248	30 (1.2)
27 C 15 (27 Mn 2)	0.22–	0.10–	1.30–					590–740	85.5–107.3	390	56.6	18	48	35.4	170–217	100 (4.0)
	0.32	0.35	1.70					690–840	100.0–121.8	450	65.3	16	48	35.4	201–248	63 (2.5)
37 C 15 (37 Mn 2)	0.32–	0.10–	1.30–					590–740	85.5–107.3	390	56.6	18	48	35.4	170–217	150 (6.0)
	0.42	0.35	1.70					690–840	100.0–121.8	490	71.1	18	48	35.4	201–248	100 (4.0)
								790–940	114.6–136.3	550	79.9	16	48	35.4	229–277	30 (1.2)
								890–1040	129.0–150.8	650	94.3	15	41	30.2	255–311	15 (0.6)
35 Mn 6 Mo 3	0.30–	0.10–	1.30–			0.20–		690–840	100.0–121.8	490	71.1	14	55	40.6	201–248	150 (6.0)
(35 Mn 2 Mo 28)	0.40	0.35	1.80			0.35		790–940	114.6–136.3	550	79.8	12	50	36.8	229–277	100 (4.0)
								890–1040	129.0–150.8	650	94.3	12	50	36.8	255–311	63 (2.5)
								990–1140	143.6–165.3	750	108.8	10	48	35.4	285–341	30 (1.2)
35 Mn 6 Mo 4	0.30–	0.10–	1.30–			0.35–		790–940	114.6–136.3	550	79.8	16	55	40.6	229–277	150 (6.0)
(35 Mn 2 Mo 45)	0.40	0.35	1.80			0.55		890–1040	129.0–150.8	650	94.3	15	55	40.6	255–311	100 (4.0)
								990–1140	143.6–165.3	750	108.9	13	48	35.4	285–341	63 (2.5)
40 Cr 4 (40 Cr 1)	0.35–	0.10–	0.60–		0.90–			690–840	100.0–121.8	490	71.1	14	55	40.6	201–248	100 (4.0)
	0.45	0.35	0.90		1.20			790–940	114.6–136.3	550	79.8	12	50	36.8	229–277	63 (2.5)
								890–1040	129.0–150.8	650	94.3	11	50	36.8	255–311	30 (1.2)
40 Cr 4 Mo 2	0.35–	0.10–	0.50–		0.90–	0.20–		700–850	101.5–123.3	490	71.1	13	55	40.6	201–248	150 (6.0)
(40 Cr 1 Mo 28)	0.45	0.35	0.80		1.20	0.35		800–950	116.0–137.8	550	79.8	12	50	36.8	229–277	100 (4.0)
								900–1050	130.5–152.3	650	94.3	11	50	36.8	255–311	63 (2.5)
								1000–1150	145.0–166.8	750	108.8	10	48	35.4	285–341	30 (1.2)
15 Cr 13 Mo 6	0.10–	0.10–	0.40–	0.30	2.90–	0.45–		690–840	100.0–121.8	490	71.1	14	55	40.6	201–248	150 (6.0)
(15 Cr 3 Mo 55)	0.20	0.35	0.70	max	3.40	0.65		790–940	114.6–136.3	550	79.9	12	50	36.8	229–277	150 (6.0)
25 Cr 13 Mo 6	0.20–	0.10–	0.40–	0.30	2.90–	0.45–		890–1040	129.0–150.8	650	94.3.	11	50	36.8	255–311	150 (6.0)
(25 Cr 3 Mo 55)	0.30	0.35	0.70	max	3.40	0.65		990–1140	143.6–165.3	750	108.8	10	48	35.4	285–341	150 (6.0)
								1090–1240	158.1–179.8	830	120.4	9	41	30.2	311–363	100 (4.0)
								1540 min	223.4 min	1240	179.8	8	14	10.3	444 min	63 (2.5)

TABLE 1–13
Chemical composition and mechanical properties of alloy steels** (*Cont.*)

Designation	Percent C	Si	Mn	Ni	Cr	Mo	V/Al	Tensile strength, σ_{st} MPa	kpsi	0.2% proof stress, min, σ_{sy} MPa	kpsi	Minimum elongation (gauge length $= 5.65\sqrt{a^*})^a$, %	Minimum Izod impact value J	ft-lbf	Brinell[#] hardness H_B	Limiting ruling section, mm (in)[+]
40 Cr 13 Mo 10 V 2	0.35 –	0.10–	0.40–	0.30	3.00–	0.90–	V: 0.15–	1340 min	194.4 min	1050	152.2	8	21	15.5	363 min	63 (2.5)
(40 Cr 3 Mo 1 V 20)	0.45	0.35	0.70	max	3.50	1.10	0.25	1540 min	223.4 min	1240	179.8	8	14	10.3	444 min	30 (1.2)
40 Cr 7 Al 10 Mo 2	0.35–	0.10–	0.40–	0.30	1.50–	0.10–	Al: 0.90–	690–840	100.0–121.8	490	71.1	18	55	40.6	201–248	150 (6.0)
(40 Cr 2 Al 1 Mo 18)	0.45	0.45	0.70	max	1.80.	0.25	1.30	790–940	114.6–136.3	550	79.8	16	55	40.6	229–277	100 (4.0)
								890–1040	129.0–150.8	650	94.3	15	48	35.4	255–311	63 (2.5)
40 Ni 14 (40 Ni 31)	0.35–	0.10–	0. 50–	3.20–	0.30			790–940	114.6–136.3	550	79.8	16	55	40.6	229–277	100 (4.0)*
	0.45	0.35	0.80	3.6	max			890–1040	129.0–150.8	650	94.3	15	55	40.6	255–311	63 (2.5)
35 Ni 5 Cr 2	0.30–	0.10–	60–90	1.00–	0.45–			690–840	100.0–121.8	490	71.1	14	55	40.6	201–248	150 (6.0)[+]
(35 Ni 1 Cr 60)	0.40	0.35		1.50	0.75			790–940	114.6–136.3	550	79.8	12	50	36.8	229–277	100 (4.0)
								890–1040	129.0–150.8	650	94.3	10	50	36.8	255–311	63 (2.5)
30 Ni 16 Cr 5	0.26–	0.10–	0.40–	3.90–	1.10–			1540 min	223.4 min	1240	179.9	8	14	10.3	444 min	(air-hardened)
(30 Ni 4 Cr 1)	0.34	0.35	0.70	4.30	1.40											150 (6.0)
																(air-hardened)
40 Ni 6 Cr 4 Mo 2	0.35–	0.10–	0.40–	1.20–	0.90–	0.10–		790–940	114.6–136.3	550	79.8	16	55	40.6	229–277	150 (6.0)
(40 Ni Cr 1 Mo 15)	0.45	0.35	0.70	1.60	1.30	0.20		890–1040	129.0–150.8	650	94.3	15	55	40.6	255–311	100 (4.0)
								990–1140	143.6–165.3	750	108.8	13	48	35.4	285–341	63 (2.5)
								1090–1240	158.1–179.8	830	120.4	13	41	30.3	311–363	30 (1.2)
40 Ni 6 Cr 4 Mo 3	0.35–	0.10–	0.40–	1.25–	0.90–	0.20–		790–940	114.6–136.3	550	79.8	16	55	40.6	229–277	150 (6.0)
(40 Ni 2 Cr 1 Mo 28)	0.45	0.35	0.70	1.75	1.30	0.35		890–1040	129.0–150.8	650	94.3	15	55	40.6	255–311	150 (6.0)
								990–1140	143.6–165.3	750	108.8	11	48	36.8	285–341	100 (4.0)
								1090–1240	158.1–179.8	830	120.4	11	41	30.3	311–363	63 (2.5)
								1190–1340	172.6–194.4	930	134.9	10	30	22.1	341–401	30 (1.2)
								1540 min	223.4 min	1240	179.8	6	11	8.1	444 min	30 (1.2)
31 Ni 10 Cr 3 Mo 6	0.27–	0.10–	0.40–	2.25–	0.50–	0.40–		890–1040	129.0–150.8	650	94.3	15	55	40.6	255–311	150 (6.0)
(31 Ni 3 Cr 65 Mo 55)	0.35	0.35	0.70	2.75	0.80	0.70		990–1140	143.6–165.3	750	108.8	12	48	35.4	285–341	150 (6.0)
								1090–1240	158.1–179.8	830	120.4	11	41	30.3	311–363	100 (4.0)
								1190–1340	172.6–194.4	930	134.9	10	35	25.8	341–401	63 (2.5)
								1540 min	223.4 min	1240	179.8	8	14	10.3	444 min	63 (2.5)

TABLE 1–13
Chemical composition and mechanical properties of alloy steels** (*Cont.*)

Designation	Percent							Tensile strength, σ_{st}		0.2% proof stress, min, σ_{sy}		Minimum elongation (gauge length $= 5.65\sqrt{a^*})^a$,	Minimum Izod impact value		Brinell[#] hardness	Limiting ruling section,
	C	Si	Mn	Ni	Cr	Mo	V/Al	MPa	kpsi	MPa	kpsi	%	J	ft-lbf	H_B	mm (in)[+]
40 Ni 10 Cr 3 Mo 6	0.36–	0.10–	0.40–	2.25–	0.50–	0.40–		990–1140	143.6–165.3	750	108.8	12	48	35.4	285–341	150 (6.0)
(40 Ni 3 Cr 65 Mo 55)	(0.44	0.35	0.70	2.75	0.80	0.70		1090–1240	158.1–179.8	830	120.4	11	41	30.3	311–363	150 (6.0)
								1190–1240	172.6–194.4	930	134.9	10	35	25.8	341–401	150 (6.0)
								1540 min	223.4 min	1240	179.8	8	14	10.3	444 min	100 (4.0)

Note: a^*, area of cross section; ** hardened and tempered condition – oil-hardened unless otherwise stated; # hardness given in this table is for guidance only; § steel designations in parentheses are old designations; + numerals in parentheses are in inches.
Source: IS 1750, 1988.

TABLE 1-14
Mechanical properties of case hardening steels in the refined and quenched condition (core properties)

	Tensile strength, σ_{st}		Minimum elongation, % (gauge length $= 5.65\sqrt{a^*}$)[a]	Izod impact value, min (if specified)			
Steel designation	**MPa**	**kpsi**		**J**	**ft-lbf**	**Limiting ruling section, mm (in)**	**Brinell hardness number, max, H_B**
10 C 4 (C 10)	490	71.1	17	54	39.8	15 (0.6)	130
14 C 4 (C 14)	490	71.1	17	54	39.9	>15 (0.6)	143
						<30 (1.2)	
10 C 8 S 11 (10 S 11)	490	71.1	17	54	39.8	30 (1.2)	143
14 C 14 S 14	588	85.4	17	40	29.7	30 (1.2)	154
(14 Mn 1 S 14)							
11 C 15	588	85.4	17	54	39.8	30 (1.2)	154
(11 Mn 2)							
15 Cr 65	588	85.4	13	47	34.7	30 (1.2)	170
17 Mn 1 Cr 95	784	113.8	10	34	25.3	30 (1.2)	207
20 Mn Cr 1	981	142.3	8	37	27.5	30 (1.2)	217
16 Ni 3 Cr 2	686	99.6	15	40	29.7	90 (3.6)	184
(16 Ni 80 Cr 60)							
16 Ni 4 Cr 3	834	121.0	12	40	29.7	30 (1.2)	217
(16 Ni 1 Cr 80)	784	113.8				60 (2.4)	
	735	106.7				90 (3.6)	
13 Ni 13 Cr 3	834	121.0	12	47	34.7	60 (2.4)	229
(13 Ni 3 Cr 80)	784	113.8				100 (4.0)	
15 Ni 4 Cr 1	1324	192.0	9	34	25.3	30 (1.2)	241
	1177	170.7				60 (2.4)	
	1128	163.2				90 (3.6)	
20 Ni 2 Mo 25	834	121.0	12	61	44.8	30 (1.2)	207
	686	99.6				60 (2.4)	
20 Ni 7 Cr 2 Mo 2	882	128.0	11	40	29.7	30 (1.2)	213
(20 Ni 55 Cr 50 Mo	784	113.8				60 (2.4)	
20)	735	106.7				90 (3.6)	
15 Ni 13 Cr 4	981	142.3	9	40	29.7	30 (1.2)	217
(15 Ni Cr 1 Mo 12)	932	135.1				90 (3.6)	
15 Ni 5 Cr 4 Mo 2	1079	156.5	9	34	25.3	30 (1.2)	217
(15 Ni 2 Cr 1 Mo.15)	932	142.3				60 (2.4)	
	932	135.1				90 (3.6)	
16 Ni 8 Cr 6 Mo 2	1324	193.0	9	34	25.3	30 (1.2)	229
(16 Ni Cr 2 Mo 20)	1177	170.7				60 (2.4)	
	1128	163.6				90 (3.6)	

[a] a^* area of cross section.
Source: IS 4432. 1967.

TABLE 1-15
Typical mechanical properties of some carburizing steels[a]

AISI No.	Ultimate tensile strength, σ_{sut} MPa	Ultimate tensile strength, σ_{sut} kpsi	Tensile yield strength, σ_{sy} MPa	Tensile yield strength, σ_{sy} kpsi	Elongation in 50 mm (2 in), %	Reduction of area, %	Hardness: Core Brinell, H_B	Hardness: Case Rockwell, R_C	Hardness: Case Thickness mm	Hardness: Case Thickness in	Izod impact energy J	Izod impact energy ft-lbf	Machin-ability
							Plain carbon						
C1015	503	73	317	46	31	71	149	62	1.22	0.048	123	91	Poor
C1020	517	75	331	48	31	71	156	62	1.17	0.046	126	93	Poor
C1022	572	83	324	47	27	66	163	62	1.17	0.046	110	81	Good
C1117	669	97	407	59	23	53	192	65	1.14	0.045	45	33	Very good
C1118	779	113	531	77	17	45	229	61	1.65	0.065	22	16	Excellent
							Alloy steels						
4320[b]	100	146	648	94	22	56	293	59	1.91	0.075	65	48	
4620[b]	793	115	531	77	22	62	235	59	1.52	0.060	106	78	
8620[b]	897	130	531	77	22	52	262	61	1.78	0.070	89	66	

[a] Average properties for 15 mm (1 in) round section treated, 12.625 mm (0.505 in) round section tested. Water-quenched and tempered at 177°C (350°F), except where indicated.
[b] Core properties for 14.125 mm (0.565 in) round section treated, 12.625 mm (0.505 in) round section tested. Oil-quenched twice, tempered at 232°C (450°F).
Source: *Modern Steels and Their Properties*, Bethlehem Steel Corp., 4th ed., 1958 and 7th ed., 1972.

TABLE 1-16
Minimum mechanical properties of some stainless steels

UNS No.	AISI No.	Tensile strength, σ_{st} MPa	Tensile strength, σ_{st} kpsi	Yield strength[a], σ_{sy} MPa	Yield strength[a], σ_{sy} kpsi	Brinell hardness, H_B	Elongation, %	Reduction in area, %	Weldability	Machinability	Application
							Annealed (room temperatures)				
Austenitic											
S30200	302	515	75	205	30	88	40		Good	Poor	General purpose, springs
S30300	303[b]	585[b]	85[b]	240[b]	35[b]		50[b]	55[b]	Poor	Good	Bolts, rivets, and nuts
S30400	304	515	75	205	30	88	40		Good	Poor	Welded structures
S30500	305	480	70	170	25	88	40		Good		General purpose
S30800	308	515	75	205	30	88	40				
S30900	309	515	75	205	30	95	40				
S31000	310	515	75	205	30	95	40		Good	Poor	Heat-exchange parts
S31008	310 S	515	75	205	30	95	40		Good	Poor	Turbine and furnace
S34800	348	515	75	205	30	88	40				Jet engine parts
S38400	384	415–550	60–80								Fasteners and cold-worked parts
							Annealed high-nitrogen				
Austenitic											
S20200	202	655	95	310	4560		40				
S21600	216	690	100	415	50	100	40				
S30452	304 HN	620	90	345		100	30				
Ferrite											
S40500	405	415	60	170	25	88 max			Excellent		
S43000	430	450	65	205	30	88 max	22[e]		Fair	Fair to good	Screw machine parts, muffler
S44600	446	515	75	275	40	95 max	20		Fair	Fair	Machine parts subjected to high-temperature corrosion
Martensite											
S40300	403	485	70	205	30	88 max	25[c]				Bolts, shafts, and machine parts
S41000	410	450	65	205	30	95 max	22[c]				Bolts, springs, cutlery, and machine parts
S41400	414	795	115	620	90		15	45			
S41800[d]	418[d]	1450[b]	210[b]	1210[b]	175[b]		18[b]	52[b]			
S42000[e]	420[e]	1720	250	1480[b]	215[b]	52R_C[b]	8[b]	25[b]			
S43100[d]	431[d]	1370[b]	198[b]	1030[b]	149[b]		16[b]	55[b]			High-strength parts used in aircraft and bolts
S44002	440 A	725[b]	105[b]	415[b]	60[b]	95[b]	20[b]				Cutlery, bearing parts, nozzles and ball bearings
S44003	440 B	740	107[b]	425[b]	62[b]	96[b]	18[b]				
S44004	440 C	760[b]	110[b]	450[b]	65[b]	97[b]	14[b]				
S50200	502[b]	485[b]	70[b]	205[b]	30[b]		30[b]	70[b]			

[a] At 0.2% offset.
[b] Typical values.
[c] 20% elongation for thickness of 1.3 mm (0.050 in) or less.
[d] Tempered at 260°C (500°F).
[e] Tempered at 205°C (400°F).
Source: *ASM Metals Handbook*, American Society for Metals, Metals Park, Ohio, 1988.

TABLE 1-17
Chemical composition and mechanical properties of some stainless, heat resisting and high alloy steels

Designation of steel	Chemical composition, %										Tensile strength, min, σ_{st}		0.2% proof stress, min, σ_{sy}		Hardness number		Elongation in 50 mm (2 in), min, %	Reduction of area, min, %
	C	Si	Mn	Ni	Cr	Mo	Ti	Nb	S max	P max	MPa	kpsi	MPa	kpsi	Brinell H_B	Rockwell R_B		
									Chromium steels									
X 04 Cr 12*	0.08 max	1.0 max	1.0 max		11.5/13.5				0.030	0.040	415 (445}#	60.2 (64.5)	205 (276)#	29.7 (40.0)	183	88	22 (20)#	(45)#
X 12 Cr 12*	0.80/0.15	1.0 max	1.0 max	1.0 max	11.5/13.5				0.030	0.040	450 (483)	65.3 (70.0)	205 (276)	29.7 (40.0)	217	95	20 (20)	(45)
X 07 Cr 17	0.12 max	1.0 max	1.0 max	1.25/2.50	15.0/17.0				0.030	0.040	450 (483)	65.3 (70.0)	205 (276)	29.7 (40.0)	183	88	22 (20)	(45)
X 40 Cr 13	0.35/0.45	1.0 max	1.0 max	1.0 max	12.0/14.0				0.030	0.040	(600 700)	(87.0 101.5)			(225)	–		
X 15 Cr 25 N	0.20 max	1.0 max	1.5 max		23.0/27.0				0.030 and $N = 0.25$ max	0.045	515 (490)	74.7 (71.1)	275 (280)	39.9 (40.6)	217 (212)	–	20 (16)	(45)
									Chromium–nickel steels									
X 02 Cr 19 Ni 10	0.03 max	1.0 max	2.0 max	8.0/12.0	17.5/20.0				0.030	0.045	485 (483)	70.3 (70.0)	170 (172)	24.7 (25.0)	183	88	40 (40)	(50)
X 04 Cr 19 Ni 9	0.08 max	1.0 max	2.0 max	8.0/10.5	17.5/20.0				0.030	0.045	515 (517)	74.7 (75.0)	205 (207)	29.7 (30.0)	183	88	40 (40)	(50)
X 07 Cr 18 Ni 9	0.15 max	1.0 max	2.0 max	8.0/10.0	17.0/19.0				0.030	0.045	515	74.7	205	29.7	183	88	40	
X 04 Cr 18 Ni 10 Nb	0.08 max	1.0 max	2.0 max	9.0/12.0	17.0/19.0			10XC- 1.0	0.030	0.045	515 (517)	74.7 (75.0)	205 (207)	29.7 (30.0)	183	88	40 (40)	(50)
X 04 Cr 18 Ni 10 Ti	0.08 max	1.0 max	2.0 max	9.0/12.0	17.0/19.0		5XC- 0.80**		0.030	0.045	515 (517)	74.7 (75.0)	205 (207)	29.7 (30.0)	183	88	40 (40)	(50)
X 04 Cr 17 Ni 12 Mo 2	0.08 max	1.0 max	2.0 max	10.0/14.0	16.0/18.0	2.0/3.0			0.030	0.045	515 (517)	74.7 (75.0)	205 (207)	29.7 (30.0)	217	95	40 (40)	(50)
X 02 Cr 17 Ni 12 Mo 2	0.08 max	1.0 max	2.0 max	10.0/14.0	16.0/18.0	2.0/3.0			0.030	0.045	485 (483)	70.3 (70.0)	170 (172)	24.7 (25.0)	217	95	40 (40)	(50)
X 04 Cr 17 Ni Mo 2 Ti 2	0.08 max	1.0 max	2.0 max	10.0/14.0	16.0/18.0	2.0/3.0	5XC- 0.80		0.030	0.045	515 (517)	74.7 (75.0)	205 (207)	29.7 (30.0)	217	95	40 (40)	(50)
X 04 Cr 19 Ni 13 Mo 3	0.03 max	1.0 max	2.0 max	11.0/15.0	18.0/20.0	3.0/4.0			0.030	0.045	515 (517)	74.7 {75.0)	205 (207)	29.7 (30.0)	217	95	35 (40)	(50)
X 20 Cr 25 Ni 20	0.25 max	2.5 max	2.0 max	18.0/21.0	24.0/26.0				0.030	0.045	515 (490)	74.7 (71.1)	210 (210)	30.5 (30.5)	217	95	40 (40)	(50)
X 07 Cr 17 Mn 12 Ni 4	0.12 max	1.0 max	10.0/14.0	3.5/5.5	16.0/18.0				0.030	0.045	550	79.8	250	36.3	217	88	45	(50)
X 40 Ni 14 Cr 14 W 3 Si 2	0.35/0.50	2.5 max	1.0 max	12.0/15.0	12.0/15.0			and	0.035 W 2.0/3.0	0.045	(785)	(113.9)	(345)	(50.0)	(269)		(35)	(40)

Notes: Annealed quenched or solution-treated condition; * for free-cutting varieties sulfur and selenium content shall be as agreed between the purchaser and the manufacturer; ** for electrode steel Nb −10C to 1.0 in place of Ti; # the mechanical properties in parentheses are for bars and flats and the properties without parentheses for plates, sheets, and strips.
Source: Compiled from IS 1570 (part 5), 1985.

TABLE 1-18
Mechanical properties of high-strength low-alloy steels

ASTM specification	Type, grade, or condition	UNS designation	Minimum tensile[a] strength,[a] σ_{st} MPa	kpsi	Minimum yield[a] strength,[a] σ_{sy} MPa	kpsi	Minimum elongation,[a] % In 200 mm (8 in)	In 50 mm (2 ln)	Intended uses
A242	Type 1	K11510	435–480	63–70	290–345	42–50	18	21	Structural members in welded, bolted, or riveted construction
A440		K12810	435–485	63–70	290–345	42–50	18	21	Structural members, primarily in bolted or riveted construction
A441		K12211	415–485	60–70	275–345	42–50	18	21	Welded, bolted, or riveted structures but primarily welded bridges
A572	Grade 42		415	60	290	42	20	24	Welded, bolted, or riveted structures, but used mainly in bolted or riveted bridges and buildings
	Grade 50		450	65	345	50	18	21	
	Grade 60		520	75	415	60	16	18	
	Grade 65		550	80	450	65	15	17	
A606	Hot-rolled		480	70	345	50		22	Structural and miscellaneous purposes where weight saving or added durability is important
	Hot-rolled and annealed or normalized		450	65	310	45		22	
	Cold-rolled		450	65	310	45		22	
A607	Grade 45		410	60	310	45		22–25	Structural and miscellaneous purposes where greater strength or weight saving is important
	Grade 50		450	65	345	50		20–22	
	Grade 60		520	75	415	60		16–18	
	Grade 70		590	85	485	70		14	
A618	Grade I	K02601	483	70	345	50	19	22	General structural purposes including
	Grade II	K12609	483	70	345	50	18	22	welded, bolted, or riveted bridges and buildings
	Grade III	K12700	448	65	345	50	18	20	
A656	Grade 1 and 2		655–793	95–115	552	80	12		Truck frames, brackets, crane booms, railcars. and other applications where weight saving is important
A690		K12249	485	70	345	50	18		Dock walls, sea walls, bulkheads, excavations, and similar structures exposed to sea water
A715	Grade 50		415	60	345	50		22–24	Structural and miscellaneous applications where high strength, weight savings, improved formability, and good weldability are important
	Grade 60		485	70	415	60		20–22	
	Grade 70		550	80	485	70		18–20	
	Grade 80		620	90	550	80		16–18	

[a] May vary with product size and mill form.

Source: *ASM Metal Handbook,* American Society for Metals, Metals Park, Ohio, 1988.

TABLE 1-19
Mechanical properties of some cast alloy, cast stainless, high-strength and iron-based super alloy steels

Materials classification		Tensile strength, σ_{st}		Yield strength, σ_{sy}		Fatigue[c] endurance limit, σ_{sj}		Elongation in 50 mm (2 in)	Modulus of elasticity E		Impact Charpy		Brinell hardness, temperature,	Rupture strength, 100 h at 538°C (1000°F)	
		MPa	kpsi	MPa	kpsi	MPa	kpsi	%	GPa	Mpsi	J	ft-lbf	°C (°F), H_B	GPa	Mpsi
							Cast Alloy Steels								
ASTM	Grade														
A352-68a	LC1[a]	448	65	241	35	138	20	24			81	60			
A219-6	WC4[a]	483	70	276	40	159	23	20			75	55			
A148-65	80-50[a]	552	80	345	50	172	25	22			65	48			
A148-1	90-60[a]	620	90	414	60	214	31	20			54	40			
A148-65	105-85[b]	724	105	586	85	244	34	17			79	58	217		
A148-65	150-125[b]	1034	150	862	125	303	44	9			41	30	311		
A148-65	120-95[b]	827	120	655	95	255	37	14			61	45	262		
A148-65	175-145[b]	1207	175	1000	145	331	48	6			32	24	352		
							Cast Stainless Steels								
ACI[d]	CB-30[d]	655	95	414	60			15			3	2			
	C-50[d]	483–669	70–97	448	65			18	200	29	61	45			
	CE-30[d]	600–669	87–97	448	65			18	172	25	14	10			
	CF-8[d]	517–586	75–85	241–276	35–40			55	193	28	95	70			
	CH-20[d]	552–607	80–88	345	50			38	193	28	20	15			
							Ultra-High-Strength Steels								
Medium carbon low alloys 4 140 M, 433OV, D 6AC, 4340		To 2068	To 300	To 1724	To 250			10			23	17			
Mod. 5 Cr-Mo-V tool steels: H-11 (Mod). H-13 (Mod)		To 2144	To 311	To 1703	To 247			6.6–12			20–30	15–22			
Maraging steels (high nickel): 18 Ni (350) Almar 302		1758	255	1689	245			8			31	23			
							High-Strength Low-Alloy (HSLA) Steels								
ASTM	SAE												*Composition*		
A607	J410C[g]	414	60	310	45			25					Cb and/or V		
A606 Types 2, 4[h]		448–483	65–70	310–345	45–50			22					(Proprietary) Cu, Cr, Mn, Ni, P, and other additions		
A607	J410CR[g]	448	65	345	50			22					Cb and or V		
715 (sheet)[i] A656 (plate)		414	60	345	50			24					(Proprietary) Cb, Ti, Zr, Si, N, V, and others		
A607	J410C[g]	483	70	379	55			20							
A607	J410C[g]	586	85	483	70			14					Cb and/or V		

TABLE 1-19
Mechanical properties of some cast alloy, cast stainless, high-strength and iron-based super alloy steels (*Cont.*)

Materials classification		Tensile strength, σ_{st}		Yield strength, σ_{sy}		Fatigue[c] endurance limit, σ_{sj}		Elongation in 50 mm (2 in)	Modulus of elasticity E		Impact Charpy		Brinell hardness, temperature, °C (°F), H_B		Rupture strength, 100 h at 538°C (1000°F)	
		MPa	kpsi	MPa	kpsi	MPa	kpsi	%	GPa	Mpsi	J	ft-lbf			GPa	Mpsi
								Iron-Based Superalloys								
Martensitic													Temperature			
AISI													°C	°F		
601	17-22A	827	120	689	100			30	21	3.08			21	70	338	49
		531	77	372	54			20					538	1000		
604	Chromalloy	682–896	125–138	655–745	95–108			7	22	3.17			21	70	517	75
		758	110	586	85								538	1000		
610	H-11	931–2137	135–310	689–1655	100–240	896	130	3–17	21	3.05	14–43	10–32	21	70	655–793	95–115
		1241	180	965	140			10					538	1000		
616	422	1034–1655	150–240	682–1207	125–175	621–758	90–100	16–19	20	2.90	14–52	10–38	21	70	400	58
		1172	170	869	126			16					538	1000		
Austenitic																
633	AM 350	103–1413	160–205	414–1207	60–175	482–689	70–100	12–38	20.3	2.94	19	14	21	70	710	103
		1130	160	745	108			9					538	1000		
635	Stainless W	1517–1551	220–225	1482–2000	215–290	372–662	54–96	1.5	20.9	3.02	5–144	4–106	21	70	220	32
		517–552	75–80	255–345	37–50			58					538	1000		
650	16-25-G	758–965	110–140	345–689	50–100			20–45	19.5	2.85	20	15	21	70	538	78
		621	90	228	33			58					538	1000		
653	17-24 Cu Mo	593–772	86–112	276–620	40–90			30–45	19.3	2.80	11–35	8–26	21	70	330	48
		448	65	200	29			37					538	1000		
660	A-286	1007–903	146	655	95			25	20	2.88	56–81	41-60	21	70	689	100
			131	607	88			19					538	1000		

[a] Normalized and tempered.
[b] Quenched and tempered.
[c] Polished specimen.
[d] Corrosion resistance.
[e] Heat resistance.
[f] Heat and corrosion resistance.
[g] Semikilled or killed.
[h] Semikilled or killed-improved corrosion resistance.
[i] Inclusion control-improved formability, killed.

Source: *Machine Design*, 1981 Materials Reference Issue, Penton/IPC, Cleveland, Ohio, Vol. 53, No. 6 (March 19, 1981).

TABLE 1-20
Mechanical properties of high tensile cast steel

Grade	Designation	Tensile strength, min, σ_{st}		Yield strength (or 0.5% proof stress), min, σ_{sy}		Reduction in area, min, %	Elongation, min, % (gauge length $5.65\sqrt{a^*}$)[a]	Brinell hardness, min, H_B	Izod impact strength, min	
		MPa	kpsi	MPa	kpsi				J	ft-lbf
1	CS 640	640	92.8	390	56.7	35	15	190	30	22.1
2	CS 700	700	101.5	560	81.2	30	14	207	30	21.1
3	CS 840	840	121.8	700	101.5	28	12	248	29	20.6
4	CS 1030	1030	149.4	850	123.3	20	8	305	20	14.5
5	CS 1230	1230	178.3	1000	145.1	12	5	355		

[a] a^*, area of cross section.
Source: IS 2644, 1979.

TABLE 1-21
Chemical composition of tool steels

Steel designation	% C	% Si	% Mn	% Cr	%Mo	%V	%W	% Ni	% Co
T 140 W 4 Cr 50	1.30–1.50	0.10–0.35	0.25–0.50	0.30–0.70			3.50–4.20		
T 133	1.25–1.40	0.10–0.30	0.20–0.35						
T 118	1.10–1.25	0.10–0.30	0.20–0.35						
T 70	0.65–0.75	0.10–0.30	0.20–0.35						
T 85	0.80–0.90	0.10–0.35	0.50–0.80						
T 75	0.70–0.80	0.10–0.35	0.50–0.80						
T 65	0.60–0.70	0.10–0.35	0.50–0.80						
T 215 Cr 12	2.00–2.30	0.10–0.35	0.25–0.50	11.0–13.0	0.80 max[a]	0.80 max[a]			
T 160 Cr 12	150–1.70	0.10–0.35	0.25–0.50	11.0–13.0	0.80 max[a]	0.80 max[a]			
T 110 W 2 Cr 1	1.00–1.20	0.10–0.35	0.90–1.30	0.90–1.30			1.25–1.75		
T 105 W 2 Cr 60 V 25	0.90–1.20	0.10–0.35	0.25–0.50	0.40–0.80	0.25 max[a]	0.20–0.30	1.25–1.75		
T 90 Mn 2 W 50 Cr 45	0.85–0.95	0.10–0.35	1.25–1.75	0.30–0.60		0.25 max	0.40–0.60		
T 105 Cr 1	0.90–1.20	0.10–0.35	0.20–0.40	1.00–1.60					
T 105 Cr 1 Mn 60	0.90–1.20	0.10–0.35	0.40–0.80	1.00–1.60					
T 55 Cr 70	0.50–0.60	0.10–0.35	0.60–0.80	0.60–0.80					
T 55 Si 2 Mn 90 Mo 33	0.50–0.60	1.50–2.00	0.80–1.00		0.25–0.40	0.12–0.20[a]			
T 50 Cr 2 V 23	0.45–0.55	0.10–0.35	0.50–0.80	0.90–1.20		0.15–0.30			
T 60 Ni 1	0.55–0.65	0.10–0.65	0.50–0.80	0.30 max				1.00–1.50	
T 30 Ni 4 Cr 1	0.26–0.34	0.10–0.35	0.40–0.70	1.10–1.40				3.90–4.30	
T 55 Ni 2 Cr 65 Mo 30	0.50–0.60	0.10–0.35	0.50–0.80	0.50–0.80	0.25–0.35			1.25–1.75	
T 33 W 9 Cr 3 V 38	0.25–0.40	0.10–0.35	0.20–0.40	2.80–3.30		0.25–0.50	8.0–10.0		
T 35 Cr 5 Mo V 1	0.30–0.40	0.80–1.20	0.25–0.50	4.75–5.25	1.20–1.60	1.00–1.20			
T 35 Cr 5 Mo W 1 V 30	0.30–0.40	0.80–1.20	0.25–0.50	4.75–5.25	1.20–1.60	0.20–0.40	1.20–1.60		
T 75 W 18 Co 6 Cr 4 V 1 Mo 75	0.70–0.80	0.10–0.35	0.20–0.40	4.00–4.50	0.50–1.00	1.50–1.50	17.50–19.00		5.00–6.00
T 83 Mo W 6 Cr 4 V 2	0.75–0.90	0.10–0.35	0.20–0.40	3.75–4.50	5.50–6.50	1.75–2.00	5.50–6.50		
T 55 W 14 Cr 3 V 45	0.50–0.60	0.20–0.35	0.20–0.40	2.80–3.30		0.30–0.60	13.00–15.00		
T 16 Ni 85 Cr 60	0.12–0.20	0.10–0.35	0.60–1.00	0.40–0.80				0.60–1.00	
T 10 Cr 5 Mo 75 V 23	0.15 max	0.10–0.35	0.25–0.50	4.75–5.25	0.50–1.00	0.15–0.30			

[a] Optional
Source: IS 1871, 1965.

TABLE 1-22
Mechanical properties of some tool steels

AISI steel designation	Condition[a]	Tensile strength, σ_{st} MPa	Tensile strength, σ_{st} kpsi	Yield strength, σ_{sy} MPa	Yield strength, σ_{sy} kpsi	Elongation, %	Hardness	Hardening temperature °C	Hardening temperature °F	Quenched media	Impact strength Charpy V-notch J	Impact strength Charpy V-notch ft-lbf	Machinability
H-11	Annealed 870°C (1600°F)[b]	690	100	365	53	25	96 R_B	1010	1850	air	14	10	Medium to high
	Tempered 540°C (1000°F)	2034	295	1724	250	9	55 R_C						
L-2	Annealed 775°C (1425°F)	710	103	510	74	25	96 R_B	855	1575	oil	28	21	High
	Tempered 205°C (400°F)	2000	290	1793	260	5	54 R_C						
L-6	Annealed 775°C (1425°F)[a]	665	95	380	55	25	93 R_B	845	1550	oil	12	9	Medium
	Tempered 315°C (600°F)	2000	290	1793	260	4	54 R_C						
P-20	Annealed 775°C (1425°F)	690	100	517	75	17	97 R_B	855	1575	oil	20	15	Medium to high
	Tempered 205°C (400°F)	1860	270	1413	205	10	52 R_C						
S-1	Annealed 800°C (1475°F)	690	100	414	60	24	96 R_B	925	1700	oil	250	184[c]	Medium
	Tempered 205°C (400°F)	2068	300	1896	275	4	57.5 R_C						
S-5	Annealed 790°C (1450°F)	724	105	440	64	25	96 R_B	870	1600	oil	206	152[c]	Medium to high
	Tempered 205°C (400°F)	2344	340	1930	280	5	59 R_C						
S-7	Annealed 830°C (1525°F)	640	93	380	55	25	95 R_R	940	1725	air	244	180	Medium
	Tempered 205°C (400°F)	2170	315	1448	210	7	58 R_C						
A-8	Annealed 845°C (1550°F)[b]	710	103	448	65	25	97 R_B	1010	1850	air	7	5	Medium
	Tempered 565°C (1050°F)	1827	265	1550	225	9	52 R_C						

[a] Single temper, oil-quenched unless otherwise indicated.
[b] Double temper, air-quenched.
[c] Charpy impact unnotched tests made on longitudinal specimens of small cross-sectional bar stock. The heat treatments listed were to develop nominal mechanical properties for hardened and tempered materials for test purposes only and may not be suitable for some applications.
Source: *Machine Design,* 1981 Materials Reference Issue, Penton/IPC, Cleveland, Ohio, Vol. 53, No. 6 (March 19, 1981).

TABLE 1-23
Properties of representative cobalt-bonded cemented carbides

Nominal composition	Grain size	Brinell Hardness H_B	Density		Transverse strength, σ_{sb}		Compressive strength, σ_{sc}		Proportional limit compressive strength, σ_{sp}		Modulus of elasticity, E		Tensile strength, σ_{st}		Impact strength		Thermal conductivity	Coefficient of linear expansion, α µm/m°C at		µin/in°F at	
			Mg/m^3	lb/in^3	MPa	kpsi	MPa	kpsi	MPa	kpsi	GPa	Mpsi	MPa	kpsi	J	in-lbf	W/m K	200°C	1000°C	400°F	1800°F
94WC-6Co	Fine	92.5–93.1	15.0	0.54	1790	260	5930	860	2550	370	614	89			1.02	9	–	4.3	5.9	2.4	3.3
	Medium	91.7–92.2	15.0	0.54	2000	290	5450	790	1930	280	648	94	1450	210	1.36	12	100	4.3	5.4	2.4	3.0
	Coarse	90.5–91.5	15.0	0.54	2210	320	5170	750	1450	210	641	93	1520	220	1.36	12	121	4.3	5.6	2.4	3.0
90WC-10Co	Fine	90.7–91.3	14.6	0.53	3100	450	5170	750	1590	230	620	90			1.69	15	–	–	–	–	–
	Coarse	87.4–88.2	14.5	0.52	2760	400	4000	580	1170	170	552	80	1340	195	2.03	18	112	5.2	–	2.9	–
84WC-16Co	Fine	89	13.9	0.50	3380	490	4070	590	970	140	524	76			3.05	27	–	–	–	–	–
	Coarse	86.0–87.5	13.9	0.50	2900	420	3860	560	700	100	524	76	1860	270	2.83	25	88	5.8	7.0	3.2	3.8
72WC-8TiC-11.5TaC-8.5Co	Medium	90.7–91.5	12.6	0.45	1720	250	5170	750	1720	250	558	81			0.90	8	50	5.8	7.0	3.2	3.8
64TiC-28WC-2TaC-2Cr_3C_2-4.0Co	Medium	94.5–95.2	6.6	0.24	690	100	4340	630										–	–		–

Source: *Metals Handbook Desk Edition*, ASM International 1985, Materials Park, OH 44073-0002 (formerly the American Society for Metals, Metals Park, OH 44073, 1985).

TABLE 1-24
Typical uses of tool steel

Steel designation	Type	Typical uses
	Cold-Work Water-Hardening Steels	
T 140 W 4 Cr 50	Fast finishing tool steel	Finishing tools with light feeds, marking tools, etc.
T 133 T 118 T 70	Carbon tool steels	Engraving tools, files, razors, shaping and wood-working tools, heading and press tools, drills, punches, chisels,shear blades, vice jaws, etc.
	Cold-Work Oil and Air-Hardening Steels	
T 215 Cr 12 T 160 Cr 12	High-carbon high-chromium tool steels	Press tools, drawing and cutter dies, shear blade thread rollers. etc.
T 110 W 2 Cr 1 T 105 W 2 Cr 60 V 25 T 90 Mn 2 W 50 Cr 45	Nondeforming tool steels	Engraving tools, press tools, gauge, tape, dies, drills, hard reamers, milling cutters, broaches, cold punches, knives. etc.
T 105 Cr 1 T 105 Cr 1 M 60	Carbon-chromium tool steels	Lathe centers, knurling tools, press tools
T 85 T 75 T 65	Carbon tool steels	Die blocks, garden and agricultural tools, etc.
T 55 Cr 70 T 55 Si 2 Mn 90 Mo 33 T 50 Cr 1 V 23	Shock-resisting tool steels	Pneumatic chisels, rivet shape, shear blades, heavy-duty punches, scarfing tools, and other tools under high shock
T 60 Ni 1 T 30 Ni 4 Cr 1 T 55 Ni 2 Cr 65 Mo 3	Nickel-chrome-molybdenum tool steels	Cold and heavy duty punches, trimming dies, scarfing tools, pneumatic chisels, etc.
	Hot-Work and High-Speed Steel	
T 33, W 9 Cr 3 V 38 T 35 Cr 5 Mo V 1 T 35 Cr 5 Mo W 1 V 30	Hot-work tool steels	Castings dies for light alloys, dies for extrusion, stamping, and forging
T 75 W 18 Co 6 Cr 4 V 1 Mo 75 T 83 Mo W 6 Cr 4 V 2 T 55 W 14 Cr 3 V 45[a]	High-speed tool steels	Drills, reamers, broaches, form cutters, milling cutters, deep-hole drills, slitting saws, high-speed and heavy-cut tools
	Low-Carbon Mold Steel	
T 16 Ni 80 Cr 60 T 10 Cr 5 bee 75 V 23	Carburizing steels	After case hardening for molds for plastic materials

[a] May also be used as hot-work steel.
Source: IS 1871, 1965.

TABLE 1-25
Mechanical properties of carbon and alloy steel bars for the production of machine parts

Steel designation	Ultimate tensile strength, σ_{sut}				Minimum elongation (gauge length $= 5.65\sqrt{a^*}$), %
	MPa##	kpsi	MPa‡	kpsi	
14 C 4 (C 14)**	363	52.6	441	64.0	26
20 C 8 (C 20)	432	62.6	510	74.0	24
30 C 8 (C 30)	490	71.1	588	85.3	21
40 C 8 (C 40)	569	82.5	667	96.7	18
45 C 8 (C 45)	618	89.6	696	101.0	15
55 C 8 (C 55 Mn <u>75</u>)	706	102.4			13
65 C 6 (C 65)	736	106.7			10
14 C 14 S 14 (14 Mn 1 S <u>14</u>)	432	62.6	530	76.8	22
11 C 10 S 25 (13 S <u>25</u>)	363	52.6	481	69.7	23

Notes: a^*, area of cross section; ## minimum; ‡ maximum; ** steel designations in parentheses are old designations
Source: IS 2073, 1970.

TABLE 1-26
Recommended hardening and tempering treatment for carbon and alloy steels

Designation	Hot-working temperature		Normalizing		Hardening		Quenching	Tempering	
	K	°C	K	°C	K	°C	K °C	K	°C
30 C 8 (C 30)	1473–1123	1200–850	1133–1163	860–890	1133–1163	860–890	Water or oil	823–923	550–660
35 C 8 (C 25 Mn 74)	1473–1123	1200–850	1123–1153	850–880	1113–1153	840–880	Water or oil	803–1033	530–760
40 C 8 (C 40)	1473–1123	1200–850	1103–1133	830–860	1103–1133	830–860	Water or oil	823–933	550–660
50 C 8 (C 50)	1473–1123	1200–850	1083–1113	810–840	1083–1113	810–840	Oil	823–933	550–660
55 C 8 (C 55 Ma 75)	1473–1123	1200–850	1083–1113	810–840	1083–1113	810–840	Oil	823–933	550–660
40 C 10 Si 8 (40 S 18)	1473–1123	1200–850	1103–1113	830–860	1103–1133	830–860	Oil	823–933	550–660
40 C 15 Si 2 (40 Mn 2 S 12)	1473–1123	1200–850	1113–1143	840–870	1113–1143	840–870	Oil	823–933	550–660
220 C 15 (20 Mn 2)	1473–1123	1200–850	1133–1173	860–900	1133–1173	860–900	Water or oil	823–933	550–660
27 C 15 (27 Mn 2)	1473–1123	1200–850	1133–1153	840–880	1133–1153	840–880	Water or oil	823–933	550–660
37 C 15 (37 Mn 2)	1473–1123	1200–850	1123–1143	850–870	1123–1143	850–870	Water or oil	823–933	550–660
40 Cr 4 (40 Cr 1)	1473–1123	1200–850	1123–1153	850–880	1123–1153	850–880	Oil	823–933	550–660
35 Mn 6 Mo 3 (35 Mn 2 Mo 28)	1473–1123	1200–850			1113–1133	840–860	Water or oil	823–933	550–660
35 Mn 6 Mo 4 (35 Mn 2 Mo 45)	1473–1123	1200–850			1113–1133	840–860	Oil	823–933	550–660
40 Cr 4 Mo 3 (40 Cr 1 Mo 28)	1473–1123	1200–850	1123–1153	850–880	1123–1153	850–880	Oil	823–933	550–660
40 Ni 14 (40 Ni 3)	1473–1123	1200–850	1103–1133	830–860	1103–1133	830–860	Oil	823–933	550–660
35 Ni Cr 2 Mo (35 Ni Cr Mo 60)	1473–1123	1200–850			1093–1123	820–850	Water or oil	823–933	550–660
40 Ni 6 Cr 4 Mo 2 (40 Ni Cr Mo 15)	1473–1123	1200–850			1103–1123	820–850	Oil	823–933	550–660
40 Ni 6 Cr 4 Mo 3 (40 Ni 2 Cr 1 Mo 28)	1473–1123	1200–850			1103–1123	830–850	Oil	823–933 or 423–473 (depending on hardness required)	550–660 or 150–200
15 Ni Cr 1 Mo 12 (31 Ni 3 Cr 65 Mo 55)	1473–1123	1200–850			1103–1123	830–850	Oil	$\leq$933	$\leq$660
30 Ni 13 Cr 5 (30 Ni 4 Cr 1)	1473–1123	1200–850			1083–1103	810–820	Air or oil	$\geq$523	$\geq$250
15 Cr 13 Mo 6 (15 Cr 3 Mo 55)	1473–1123	1200–850			1163–1183	890–910	Oil	823–973[a]	550–700[a]
25 Cr 13 Mo 6 (25 Cr 3 Mo 55)	1473–1123	1200–850			1163–1183	890–910	Oil	823–973[a]	550–700[a]
40 Cr 13 Mo 10 V 2 (40 Cr 3 Mo 1 V 20)	1473–1123	1200–850			1173–1213	900–940	Oil	843–923	570–650
40 Cr 7 Al 10 Mo 2 (40 Cr 2 Al 1 Mo 18)	1473–1123	1200–850			1123–1173	850–900	Oil	823–973	550–700
55 Cr 70)	1473–1123	1200–850	1073–1123	800–850	1073–1123	800–850	Oil	773–973	500–700
105 Cr 4 (105 Cr 1)	1373–1123	1100–850			1093–1133	820–860	Water or oil	>423	>150 in oil
105 Cr 1 Mn 60	1373–1123	1100–850			1073–1113	800–840	Water or oil	403–453	130–180

[a] Stabilization 823 K (550°C).
Source: IS 1871, 1965.

TABLE 1-27
Mechanical properties of some as-cast austenitic manganese steels

Composition, %					Section		Tensile strength, σ_{st}		Yield strength, σ_{sy} (0.2% offset)		Brinell hardness, H_B	Elongation in 50 mm, %	Reduction in area, %	Impact strength Charpy [b]	
C	Mn	Si	Other	Form	mm	in	MPa	kpsi	MPa	kpsi				J	ft-lbf
									Plain manganese steels						
0.85	11.2	0.57		Round	25	1	440	64	–	–	–	14.5	–	–	–
1.11	12.7	0.54		Round	25	1	450	65	360	52	–	4	–	–	–
1.28	12.5	0.94		Keel block	100	4	330[a]	48[a]	–	–	245	1[a]	–	3.4	2.5
									1 Mo manganese steels						
0.83	11.6	0.38	0.96 Mo	Round	25	1	695	101	345	50	163	30	29	–	–
1.16	13.6	0.60	1.10 Mo	Round	25	1	560	81	400	58	185	13	15	–	–
0.93	13.6	0.67	0.96 Mo	Plate	25	1	510	74	365	53	188	11	16	72	53
0.98	12.6	0.6	0.87 Mo	Plate	50	2	435[a]	63[a]	–	–	–	4[a]	–	–	–
									2 Mo manganese steels						
0.52	14.3	1.47	2.4 Mo	Round	25	1	600	87	370	54	220	15.5	13	–	–
0.75	14.1	0.99	2.0 Mo	Round	25	1	745	108	365	53	183	34.5	27	–	–
1.24	14.1	0.64	3.0 Mo	Round	25	1	600	87	440	64	235	7.5	10	–	–
									3.5 Ni manganese steel						
0.75	13.0	0.95	3.65 Ni	Round	25	1	655	95	295	43	150	36	26	–	–
									6 Mn-1 Mo alloys						
0.90	5.8	0.37	1.46 Mo	Mill liner	100	4	340	49	325	47	181	2	–	9	7
0.89	6.3	0.6	1.20 Mo	Plate	100	4	330[a]	48[a]	–			1[a]	–	–	–

[a] Properties converted from transverse bend tests on 6 × 13 mm ($\frac{1}{4} \times \frac{1}{2}$ in) bars cut from castings and broken by center loading across 25 mm (1 in) span.
[b] Charpy V-notch.
Source: *Metals Handbook Desk Edition*, ASM International, 1985, Materials Park, OH 44073-0002 (formerly the American Society for Metals, Metals Park, OH 44073, 1985).

TABLE 1-28
Mechanical properties, fabrication characteristics,[a] and typical uses of some aluminum alloys[b]

Alloy no.		Ultimate tensile strength, σ_{sut} MPa	kpsi	Tensile yield strength[d], σ_{syt} MPa	kpsi	Compressive yield strength,[d] σ_{syc} MPa	kpsi	Shear strength, τ_s MPa	kpsi	Endurance limit in reversed bending, σ_{sfb} MPa	kpsi	Brinell hardness 4.9 kN (500 kgf) load on 10-mm ball, H_B	Modulus of elasticity,[e] E GPa	Mpsi	Elongation in 50 mm (2 in), %	Corrosion resistance	Machi-ability	Welding Gas	Welding Arc	Welding Resis-tance	Uses
												Sand casting alloys									
201.0	-T 43	414	60	255	37										17	4	1		2		Aircraft structural components
	-T 6	448	65	379	55	386	56	290	42			130			8	4	1		2		
240.0	-F	235	34	200	29	207	30					90			1.0	4	3		4		
295.0	-T 4	221	32	110	16	117	17	179	26	48	7	60	69	10.0	8.5	3	2		2		Crankcases, spring hangers, housing, wheels
	-T 6	250	36	165	24	172	25	217	31	52	7.5	75	69	10.0	5.0	3	2		2		
319.0	-F	186	27	124	18	131	19	152	22	69	10	70	74	10.7	2.0	3	3		2		
	-T 6	250	26	164	24	172	25	200	29	76	11	80	74	10.7	2.0	3	3		2		
C 355.0	-T6	269	39	200	29							85			5.0	3	3		2		Air compressor fitting, crankcase, gear housing
356.0	-T 6	228	33	164	24	172	25	179	26	59	8.5	70	72	10.5	3.5	3	3		2		Cylinder heads, impellers, timing gears, water jackets, meter parts
A 390.0	-F	179	26	179	26							100	82	11.9	<1.0	2	4		2		Automotive engine blocks, pulleys, brake shoes, pumps
	-T 6	278	40	278	40					90	13	140			<1.0	2	4		2		
520.0	-T4	331	48	179	26	186	27	234	34	55	8	75	65	9.5	16	1	1		5		
A 535.0	-F	250	36	124	18							65			9.0	1	1		4		Aircraft fittings and components, levers, brackets
												Permanent mold casting									
355.0	-T 6	290	42	185	27	185	27	235	34	69	10	90			4.0	3	3		2		Timing gears, impellers, compressor and aircraft and missile components requiring high strength
C 355.0	-T61	303	44	234	34	248	36	221	32	97	14	90			3.0	3	3		2		
A 356.0	-T 61	283	41	207	30	221	32	193	28	90	13	90	72	10.5	10.0	2	3		2		Machine-tool parts, aircraft wheels, pump parts, marine hardware, valve bodies
513.0	-F	186	27	110	16	117	17	152	22	69	10	60			7.0	1	1		5		Ornamental hardware and architectural fittings
												Wrought alloys									
1100	-O	90	13	35	5			60	9	35	5	23			35	A	E	A	A	B	Sheet metal work, spun holloware, fin stock
	-H 14	125	18	115	17			75	11	50	7	32			9	A	D	A	A	A	
	-H 18	165	24	150	22			90	13	60	9	44			5	A	D	A	A	A	
2011	-T 3	380	55	295	43			220	32	125	18	95			15	D	A	D	D	D	Screw machine products
	-T 6	395	57	270	39			235	34	125	18	97			17						
2014	-O	185	27	95	14			125	18	90	13	45			18		D	D	D	B	Truck frames, aircraft structures
-T 4.	-T 451	425	62	290	42			260	38	140	20	105			20	C	B	D	B	B	
-T 6.	-T 651	482	70	415	60			290	42	125	18	135			13	C	B	D	B	B	
2017	-O	180	26	70	10			125	18	90	13	45			22						
-T 4.	-T 451	425	62	275	40			260	38	125	18	105			22						
2024	-O	185	27	75	11			125	18	90	13	47			20	–	D	D	D	D	Truck wheels, screw-machine products, aircraft structure
-T 4.	-T 351	470	68	325	47			285	41	140	20	120			20	C	B	C	B	B	
	-T 3	485	70	345	50			280	40	140	20	120			18	D	B	C	B	B	
	-T 86	515	75	490	71			310	45	125	18	135			6	D	B	D	C	B	

TABLE 1-28
Mechanical properties, fabrication characteristics,[a] and typical uses of some aluminum alloys[b] (*Cont.*)

Alloy no.		Ultimate tensile strength, σ_{sut}		Tensile yield strength[d], σ_{syt}		Compressive yield strength,[d] σ_{syc}		Shear strength, τ_s		Endurance limit in reversed bending, σ_{sfb}		Brinell hardness 4.9 kN (500 kgf) load on 10-mm ball, H_B	Modulus of elasticity,[e] E		Elongation in 50 mm (2 in), %	Corrosion resistance	Machi-ability	Welding			Uses
		MPa	kpsi	MPa	kpsi	MPa	kpsi	MPa	kpsi	MPa	kpsi		GPa	Mpsi				Gas	Arc	Resis-tance	
3003	-O	110	16	40	6			75	11	50	7	28			30	A	E	A	A	B	Pressure vessels, storage tanks, heat-exchanger tubes, chemical equipments, cooking utensils
	-H 14	150	22	145	21			95	14	60	9	40			8	A	D	A	A	A	
	-H 18	200	29	185	27			110	16	70	10	55			4	A	D	A	A	A	
3004	-O	180	26	70	10			110	16	95	14	45			20	A	D	B	A	B	Trailer panel sheet, storage tanks, sheet metal works
	-H 34	240	35	200	29			125	18	105	15	63			9	A	C	B	A	A	
	-H 38	285	41	250	36			145	21	110	16	77			5	A	C	B	A	A	
5052	-O	195	28	90	13			125	18	110	16	47			25	A	D	A	A	B	Hydraulic tube, appliances, bus body sheet, sheet metal work, welded structures, boat sheet
	-H 34	260	38	215	31			145	21	125	18	68			10	A	C	A	A	A	
	-H 38	290	42	255	37			165	24	140	20	77			7	A	C	A	A	A	
6061	-O	125	18	55	8			80	12	60	9	30			25	B	D	A	A	B	Heavy-duty structures requiring good corrosion resistance, truck and marine, railroad car, furniture, pipeline applications
	-T 6	310	45	275	40			205	30	95	14	95			12	B	C	A	A	A	
6063	-O	90	13	50	7			70	10	55	8	25				A		A	A	A	Pipe, railing, furniture, architectural extrusions
	-T 6	240	35	215	31			150	22	70	10	73			12	A	C	A	A	A	
7075	-O	230	38	105	15			150	22	115	17	60			17	–	D	D	C	B	Fin stock, cladding alloy
	-T 6	570	83	505	73			330	48	160	23	150			11	C	B	D	C	B	Aircraft and other structures

[a] For ratings of characteristics, 1 is the best and 5 is the poorest of the alloys listed. Ratings A through D are relative ratings in decreasing order of merit.
[b] Average of tensile and hardness values determined by tests on standard 12.5-mm ($\frac{1}{2}$-in) diameter test specimens.
[c] Endurance limits on 500 million cycles of completely reversed stresses using rotating beam-type machine and specimen.
[d] At 0.2% offset.
[e] Average of tension and compression moduli.

Key: Temper designations: F, as cast; O, annealed; Hxx, strain hardened; T1, cooled from an elevated temperature shaping process and naturally aged; T2, cooled from an elevated temperature shaping process, cold-worked and naturally aged; T3, solution heat-treated and cold worked and naturally aged; T4, solution heat-treated and naturally aged; T5, cooled from an elevated temperature shaping process and artificially aged; T6, solution heat-treated and artificially aged; T7, solution heat-treated and stabilized; T8, solution heat-treated, cold-worked and artificially aged; TX 51, stress-relieved by stretching.

Source: *ASM Metals Handbook*, American Society for Metals, Metals Park, Ohio, 1988.

TABLE 1-29
Chemical composition and mechanical properties of cast aluminum alloy[5,6,7]

Designation			Chemical composition, percent													Mechanical properties				
																Tensile strength, σ_{st}				
IS new	IS old	BS	Cu	Mg	Si	Fe	Mn	Ni	Zn	Ti	Ti + Nb	Pb	Sn	Al	Condition	MPa	kpsi	Elongation %	Brinell hardness, H_B	Test piece
2447	A-1	LM1	6.0–8.0	0.15	2.0–4.0	1.0	0.6	0.5	2.0–4.0	0.2**		0.3	0.20		As cast	124*	18.0			Sand-cast
																154*	22.3			Chill-cast
4520	A-2	LM2	0.7–2.5	0.3	9.0–11.15	1.0	0.5	1.0	1.2		0.2*	0.3	0.20		As cast	124	18.0			Sand-cast
														R		147*	21.3			Chill-cast
4223	A-4	LM4	2.0–4.0	0.15	4.0–6.0	0.8	0.3–0.7	0.3	0.5	0.2*		0.1	0.05		As cast	139*	20.2	2		Sand-cast
														E		154*	22.3	2		Chill-cast
5230	A-5	LM5	0.1	3.0–6.0	0.3	0.6	0.3–0.7	0.1	0.1	0.2**	0.2*	0.05	0.05		As cast	139*	20.2	3		Sand-cast
														M		170*	24.6	5		Chill-cast
4600	A-6	LM6	0.1	0.1	10.0–13.0	0.6	0.5	0.1	0.1	0.2**		0.1	0.05		As cast	162*	23.5	5		Sand-cast
														A		185*	26.9	7		Chill-cast
4250	A-8	LM8	0.1	0.3–0.8	3.5 –6.0	0.6	0.5	0.1	0.1	0.2**	0.2	0.1	0.05		As cast	124	18.0*	2		Sand-cast
														I		162	23.5*	3		Chill-cast
																162	23.5*	2.5		
														N		232	33.6*	5		
																147	21.3*	1		
														D		185	26.9*	2		
																232	33.6*			
														E		278	40.3*	2		
4635	A-9	LM9	0.1	0.2–0.6	10.0–13.0	0.6	0.3–0.7	0.1	0.1	0.2**	0.2	0.1	0.05		Precipitation-	170	24.6	1.5		Sand-cast
														R	treated	231	36.4	2		Chill-cast
5500	A-10	LM10	0.1	9.5–11.0	0.25	0.35	0.1	0.1	0.1	0.2**	0.2	0.05	0.05		Solution-	278*	40.3	8		Sand-cast
															treated	307*	44.8	12		Chill-cast
2280	A-11	LM11	4.0–5.0	0.1	0.25	0.25	0.1	0.1	0.1	0.3*	0.05–0.3	0.05	0.05		Solution-	216	31.3	7		Sand-cast
															treated	263	38.1	13		Chill-cast
															WP	278	40.3*	4		
																309	44.8*	9		
2585	A-12	LM12	9.0–10.5	0.15–0.35	2.0	0.5–1.5	0.6	0.5	0.1			0.1	0.10		Fully heat-				100	
															treated					
	BS 1490 (LM12)		9.0–11.5	0.2–0.4	2.5	1.0	0.6	0.5	0.8	0.2**		0.1	0.1		WP	278	40.3**			
4685	A-13	LM 13	0.5–1.3	0.8–1.5	11.0–13.0	0.8	0.5	2.0–3.0	0.1	0.2**	0.2	0.1	0.10		Fullly heat-	170	24.6		100	Sand-cast
															treated	247	35.9		100	Chill-cast
	A13 (special)														WP	170	24.6			Sand-cast
																278	40.3			Chill-cast
															WP	139	20.2		65	Sand-cast
																201	29.2		65	Chill-cast

TABLE 1-29
Chemical composition and mechanical properties of cast aluminum alloy (*Cont.*)

Designation			Chemical composition, percent													Mechanical properties				
																Tensile strength, σ_{st}		Elongation	Brinell hardness,	
IS new	IS old	BS	Cu	Mg	Si	Fe	Mn	Ni	Zn	Ti	Ti + Nb	Pb	Sn	Al	Condition	MPa	kpsi	%	H_B	Test piece
2285	A-14	LM 14	3.5–4.5	1.2–1.7	0.6	0.6	0.6	1.8–2.3	0.1	0.2^{*}		0.05	0.05		Fully heat-	216	31.3		100	Sand-cast
															treated	278	40.3		100	Chill-cast
	A-14 (special)														WP	185	26.9		75	Sand-cast
															Solution-	232	33.6		75	Chill-cast
															treated					
4225	A-16	LM16	1.0–1.5	0.4–0.6	4.5–5.5	0.6	0.5	0.25	0.1	0.2^{**}		0.05	0.05			170	24.6	2		Sand-cast
												0.1^{**}			WP	201	29.2	3		Chill-cast
															WP	232	33.6			Sand-cast
															WP	263	38.1			Chill-cast
															WP	232	33.8			Sand-cast
															As cast	278	40.3			Chill-cast
4300	A-18	LM18	0.1	0.1	4.5–6.0	0.6	0.5	0.1	0.1	0.2^{**}	0.2	0.1	0.05			116	16.8	3		Sand-cast
																139	20.2	4		Chill-cast
4223	A-22	LM22	2.8–3.8	0.05	4.0–6.0	0.7	0.3–0.6	0.15	0.15	0.2^{**}	0.2	0.05	0.05		Solution (W)-	247	35.9	8		Chill-cast
															treated					
													0.1^{**}							
4420	A-24	LM24	3.0–4.0	0.1	7.5–9.5	1.3	0.5	0.5	1.0	0.2^{**}		0.3	0.20		As cast	177	25.7	1.5		Chill-cast
									3.0^{**}											

Notes: IS: Sp-1-1967 Specification of Aluminum Alloy Castings and BS 1490 (from LM 1 to LM 24) are same.
* Refer to both Indian Standards and British Standards; ** refer to British Standards, BS 1490 only.
Source IS Sp-1, 1967.

TABLE 1-30
Chemical composition and mechanical properties of wrought aluminum and aluminum alloys for general engineering purposes[6]

	Chemical composition, %									Size			0.2% proof stress, min, σ_{sp}		Tensile strength, min, σ_{st}		
Designation	Al	Cu	Mg	Si	Fe	Mn	Zn	Ti or others	Cr	Condition	Over mm (in)	Up to and including mm (in)	MPa	kpsi	MPa	kpsi	Elongation, % (min)
19000	99 min	0.1	0.2	0.5	0.7	0.1	0.1	–	–	M[a]			20	2.9	65	9.4	18
										O					110#	16.0	25
19500	99.5 min	0.05	–	0.3	0.4	0.05	0.1	–	–	M[a]			18	2.6	65	9.4	23
										O					100#	14.5	25
19600										M[a]			17	2.5	65	9.4	23
										M[a]			90	13	150	21.6	12
										O			175	25.4	240#	34.8	12
24345	Remainder	3.8–5.0	0.2–0.8	0.5–1.2	0.7	0.3–1.2	0.2	0.3*	0.3*	W	10 (0.4)	10 (0.4)	225	32.6	375	54.4	10
											10 (0.4)	75 (3.0)	235	34.1	385	55.8	10
											75 (3.0)	150 (6.0)	235	34.1	385	55.8	8
											150 (6.0)	200 (8.0)	225	32.6	375	54.4	8
										WP	–	10 (0.4)	375	54.4	430	62.4	6
											10 (0.4)	25 (1.0)	400	58.0	460	66.7	6
											25 (1.0)	75 (3.0)	420	60.9	480	69.6	6
											75 (3.0)	150 (6.0)	405	58.7	460	66.7	6
											150 (6.0)	200 (8.0)	380	55.1	430	62.4	6
										M[a]	–	–	90	13.0	150	21.0	12
										O	–	–	175#	25.0	240	34.8	12
											–	10 (0.4)	220	31.9	375	54.4	10
24534	Remainder	3.5–4.7	0.4–1.2	0.2–0.7	0.7	0.4–1.2	0.2	0.3	–	W	10 (0.4)	75 (3.0)	235	34.1	385	55.8	10
											75 (3.0)	150 (6.0)	235	34.1	385	55.8	8
											150 (6.0)	200 (8.0)	225	32.6	375	54.4	8
43000	Remainder	0.1	0.2	4.5– 6.00	0.6	0.5	0.2	–	–	M[a]	–	15 (0.6)	–	–	90	13.0	18
										O	–	15 (0.6)	–	–	130#	18.9	18
46000	Remainder	0.1	0.2	10.0–13.0	0.6	0.5	0.2	–	–	M[a]	–	15 (0.6)	–	–	100	14.5	10
										O	–	15 (0.6)	–	–	150#	21.8	12
52000	Remainder	0.1	1.7–2.6	0.6	0.5	0.5	0.2	0.2	0.25	M[a]	–	150 (6.0)	70	10.2	160	23.2	14
										O	–	50 (2.0)			240#	34.8	18
53000	Remainder	0.1	2.8–4.0	0.6	0.5	0.5	0.2	0.2	0.25	M[a]	–	150 (6.0)	100	14.5	215	31.2	14
											50 (2.0)	150 (6.0)	100	14.5	200	29.0	14
										O	–	150 (6.0)	–	–	260#	37.7	10
54300	Remainder	0.1	4.0–4.9	0.4	0.7	0.5–1.0	0.2	0.2	0.25	M[a]	–	150 (6.0)	130	18.9	275	40.0	11
										O	–	150 (6.0)	125	18.1	350	50.8	13
63400	Remainder	0.1	0.4–0.9	0.3–0.7	0.6	0.3	0.2	0.2	0.1	M[a]	All sizes	–	–	–	110	16.0	13
										O	–	–	–	–	130#	18.8	18
										W	–	150 (6.0)	80	11.6	140	20.3	14
											150 (6.0)	200 (8.0)	80	11.6	125	18.1	13

TABLE 1-30
Chemical composition and mechanical properties of wrought aluminum and aluminum alloys for general engineering purposes (*Cont.*)

	Chemical composition, %									Size			0.2% proof stress, min, σ_{sp}		Tensile strength, min, σ_{st}		
Designation	Al	Cu	Mg	Si	Fe	Mn	Zn	Ti or others	Cr	Condition	Over mm (in)	Up to and including mm (in)	MPa	kpsi	MPa	kpsi	Elongation, % (min)
										P	–	23 (0.12)	140	20.3	170	24.7	7
												12 (0.5)	110	16.0	150	21.8	7
										WP	–	150 (6.0)	150	21.8	185	26.8	7
											150 (6.0)	200 (8.0)	130	18.9	150	21.8	6
64423	Remainder	0.5–1.0	0.5–1.3	0.7–1.3	0.8	1.0				M[a]	–	–	–	–	120	17.4	10
										O	–	–	125#	18.1	215#	31.2	15
										W	–	–	155	22.5	265	38.4	13
										WP	–	–	265	38.4	330	47.9	7
64430	Remainder	0.1	0.4–1.2	0.6–1.3	0.6	0.4–1.0	1.0	0.2	0.25	M[a]	All sizes	–	80	11.6	110	16.0	12
										O	–	–	–	–	150#	21.8	16
										W	–	150 (6.0)	120	18.1	185	26.8	14
										WP	150 (6.0)	200 (8.0)	100	14.5	170	24.7	12
											–	5 (0.2)	255	37.0	295	42.8	7
											5 (0.2)	75 (3.0)	270	39.2	310	45.0	7
											75 (3.0)	150 (6.0)	270	39.2	295	42.8	7
											150 (6.0)	200 (8.0)	240	34.8	280	40.6	6
65032	Remainder	0.15–0.4	0.7–1.2	0.4–0.8	0.7	0.2–0.8	0.2	0.2	0.15–0.35	M[a]	All sizes		50	7.3	110	16	12
										O	–	15 (0.6)	115#	16.7	150#	21.8	16
										W	–	150 (6.0)	115	22.5	185	26.8	14
											150 (6.0)	200 (8.0)	100	14.5	170	24.7	12
										WP	–	150 (6.0)	235	34.0	280	40.6	7
											150 (6.0)	200 (8.0)	200	29.0	245	35.5	6
74530	Remainder	0.2	1.0– 1. 5	0.4–0.8	0.7	0.2–0.7	4–5	0.2	0.2	W	–	6 (0.24)	220	31.4	255	37.0	9
										(Naturally	6 (0.24)	75 (3.0)	230	33.6	275	40.0	9
										aged for 30	75 (3.0)	150 (6.0)	220	31.4	265	38.4	9
										days)							
										WP	–	6 (0.24)	245	35.5	285	41.3	7
											6 (0.24)	75 (3.0)	26-	37.7	310	45.0	7
												150 (6.0)	245	35.5	290	42.1	7
76528										WP	All sizes	–	–	–	290#	42.1	10
											–	6 (0.24)	430	62.4	500	72.5	6
											6 (0.24)	75 (3.0)	455	66.6	530	78.9	6
											15 (0.6)	150 (6.0)	430	62.4	500	72.5	6

[a] Properties in M (as-cast) temper are only typical values and are given for information only.
Key: # Maximum, M – as-cast condition; R – stress-relieved only; P – precipitation-treated; W – solution-treated, WP – solution-treated and precipitation treated; WPS – fully heat treated plus stabilization.
Source: IS 733, 1983.

TABLE 1-31
Typical mechanical properties and uses of some copper alloys[4]

Alloy name	UNS no.	Composition,[a]	Ultimate tensile strength, σ_{sut} MPa	Ultimate tensile strength, σ_{sut} kpsi	Tensile yield[b] strength, σ_{syt} MPa	Tensile yield[b] strength, σ_{syt} kpsi	Elongation in 50 mm (2 in), %	Hardness: Brinell, 4.9 kN (500-kgf load) H_B	Hardness: Rockwell,[a] R	Machinability rating[c]	Typical uses
							Cast Alloys				
Leaded red brass	C 83600	85 Cu, 5 Sn, 5 Pb, 5 Zn	255	37	117	17	30	60		84	Valves, flanges, pipe fittings, pump castings, water pump impellers and housings, small gears, ornamental fittings
Leaded yellow brass	C 85400	67 Cu, 1 Sn, 3 Pb, 29 Zn	234	34	83	12	25	50		80	General-purpose yellow casting alloy, furniture hardware, radiator fittings, ship trimmings, clocks, battery clamps, valves, and fittings
Manganese bronze	C 86300	63 Cu, 25 Zn, 3 Fe, 6 Al, 3 Mn	793	115	572	83	15	225[d]		8	Extra-heavy-duty, high-strength alloy, large valve stems, gears, cams, slow heavy-load bearings, screw-down nuts, hydraulic cylinder parts
Silicon bronze	C 87200	89 Cu min, 4 Si	379	55	172	25	30	85		40	Bearings, bells, impellers, pump and valve components, marine fittings, corrosion-resistant castings
Silicon brass	C 87500	82 Cu, 14 Zn, 4 Si	462	67	207	30	21	115 134[d]		50	Bearings, gears, impeller, rocker arms, valve stems, small boat propellers
Tin bronze	C 90500	88 Cu, 10 Sn, 2 Zn	310	45	152	22	25	75		30	Bearings, bushings, piston rings, valve components, steam fittings, gears
Leaded tin bronze	C 92200	88 Cu, 6 Sn, 1.5 Pb, 4.5 Zn	276	40	138	20	30	65		42	Valves, fittings and pressure-containing parts for use up to 288°C (550°F), bolts, nuts, gears, pump piston, expansion joints
Leaded tin nickel bronze	C 92900	84 Cu, 10 Sn, 2.5 Pb, 3.5 Ni	324	47	179	26	20	80		40	Gears, wear plates, cams, guides
High-leaded tin bronze	C 93700	80 Cu, 10 Sn, 10 Pb	241	35	124	18	20	60		80	Bearings for high-speed and heavy-pressure pumps, impellers, pressure-tight castings
Aluminum bronze	C 95500	81 Cu, 4 Ni, 4 Fe, 11 AI	689–827	100–120	303–469	44–68	12–10	192–230[d]		50	Valve guides and seats in aircraft engines, bushings, rolling mill bearings, washers, chemical plant equipment, chains, hooks, marine propellers, gears, worms
Copper-nickel	C 96300	79.3 Cu, 20 Ni, 0.7 Fe	517	75	379	55	10	150		15	Marine fittings, sleeves and seawater corrosion resistance parts
Nickel-silver	C 97800	66 Cu, 5 Sn, 2 Pb, 25 Ni, 2 Zn	379	55	207	30	15	130[d]		60	Valves and valve seats, musical instrument components, sanitary and ornamental hardware
Special alloy	C 99400	90.4 Cu, 2.2 Ni, 2.0 Fe, 1.2 Al, 1.2 Si, 3.0 Zn	455–545	66–79	234–372	34–54	25	125–170[d]		50	Valve stems, marine uses, propeller wheels, mining equipment gears
							Wrought Alloys				
Cadmium copper	C 16200	99.0 Cu, 1.0 Cd	241–689	35–100	48–476	7–69	57–1			20	Trolley wire, spring contacts, railbands, high-strength transmission lines, switch gear components, and ware-guide
Beryllium copper	C 17000	99.5 Cu, 1.7 Be, 0.20 Co	483-1310	70-190	221-1172	32-170	45-3		R_B98	20	Bellows, diaphragms, fuse clips, fasteners, lock washers, springs, valves, welding equipment, bourdon tubing
Leaded beryllium copper	C 17300	99.5 Cu, 1.9 Be, 0.4 Pb	469-1479	68-200	172-1255	25-182	48-3		R_B77	50	Bellows, diaphragms, fuse clips, fasteners, lock washers, springs, valves, welding equipment, switch parts, roll pins

TABLE 1-31
Typical mechanical properties and uses of some copper alloys (*Cont.*)

Alloy name	UNS no.	Composition,[a]	Ultimate tensile strength, σ_{sut} MPa	Ultimate tensile strength, σ_{sut} kpsi	Tensile yield[b] strength, σ_{syt} MPa	Tensile yield[b] strength, σ_{syt} kpsi	Elongation in 50 mm (2 in), %	Hardness: Brinell, 4.9 kN (500-kgf load) H_B	Hardness: Rockwell,[a] R	Machin-ability rating[c]	Typical uses
Guilding brass (95%)	C 21000	95.0 Cu, 5.0 Zn	234–441	34–64	69–400	10–58	45–4		$64R_B$–$46R_F$	20	Coins, medals, bullet jackets, fuse caps, primers, jewellery base for gold plate
Commercial bronze (90%)	C 22000	90.0 Cu, 10.0 Zn	255–496	37–72	69–427	10–62	50–3		$70R_B$–$53R_F$	20	Etching bronze, grillwork, screen cloth, lipstick cases, marine hardware, screws, rivets
Red brass (85%)	C 23000	85.0 Cu, 15.0 Zn	269–724	39–105	69–434	10–63	55–3		$77R_B$–$55R_F$	30	Conduit, sockets, fasteners, fire extinguishers, condenser and heat-exchanger tubing, radiator cores
Cartridge brass (70%)	C 26000	70.0 Cu, 30.0 Zn	303–896	44–130	76–448	11–65	66–3		$82R_B$–$64R_F$	30	Radiator cores and tanks, flashlight shells, lamp fixtures, fasteners, locks, hinges, ammunition components, rivets
Yellow brass	C 26800	65.0 Cu, 35.0 Zn	317–883	46–128	97–427	14–62	65–3		$80R_B$–$64R_F$	30	Radiator cores and tanks, flashlight shells, lamp fixtures, fasteners, locks, hinges, rivets
Muntz metal	C 28000	60.0 Cu, 41.0 Zn	372– 510	54–74	145–379	21–55	52–10		$85R_F$–$80R_B$	40	Architectural, large nuts and bolts, brazing rods, condenser plates, heat-exchanger and condenser tubing, hot forgings
Medium leaded brass	C 34000	65.0 Cu. 1.0 Pb, 34.0 Zn	324–607	47–88	103–414	15–60	60–7			70	Butts, gears, nuts, rivets, screws, dials, engravings
Free-cutting brass	C 36000	61.5 Cu, 3.0 Pb, 35.5 Zn	338–469	49–68	124–310	18–45	53–18			100	Gears, pinions, automatic high-speed screws, machine parts
Forging brass	C 37700	59.0 Cu, 2.0 Pb, 39.0 Zn	359	52	138	20	45			80	Forgings and pressings of all kinds
Admiralty brass	C 44300 C 44400 C 44500	71.0 Cu, 28.0 Zn, 1.0 Sn	331–379	48–55	124–152	18–22	65–60			30	Ferrules, condenser, evaporator and heat-exchanger tubing, distiller tubing
Naval brass	C 46400 to C 46700	60.0 Cu, 39.25 Zn, 0.75 Sn	379–607	55–88	172–455	25–66	50–17		90-$82R_B$	30	Aircraft turn buckle barrels, balls, bolts, nuts, marine hardware, propeller, rivets, shafts, valve stems, welding rods, condenser plate
Phosphor bronze (5% A)	C 51000	95.0 Cu. 5.0 Sn, trace P	324– 965	47–140	131–552	19–80	64–2			20	Bellows, bourdon tubing, clutch disks, cotter pins, diaphragms, fasteners, lock washers, chemical hardware, textile machinery
High-silicon bronze -A	C 65500	97.0 Cu, 3.0 Si	386– 1000	56–145	145–483	21–70	63–3			30	Hydraulic pressure liners, anchor screws, bolts, cap screws, machine screws, nuts, rivets, U-bolts, electrical conduits, welding rod
Manganese bronze–A	C 67500	58.5 Cu, 1.4 Fe, 39.0 Zn, 1.0 Sn, 0. 1 Mn	448– 579	65–84	207–414	30–60	33–19			30	Clutch disks, pump rods, shafting, balls, valve stems and bodies
Copper-nickel (30%)	C 71500	70.0 Cu, 30.0 Ni	372–517	54–75	138–483	20–70	45–15			20	Condensers, condenser plates, distiller tubing, evaporator and heat-exchanger tubing, ferrules, salt water piping
Nickel-silver 55-18	C 77000	55.0 Cu, 27.0 Zn, 18.0 Ni	414–1000	60—145	186–621	27–90	40–2			30	Optical goods, springs, and resistance wires

[a] Nominal composition. unless otherwise noted. [b] All yield strengths are calculated by 0.5 percent offset method. [c] Machinability rating expressed as a percentage of the machinability of C 36000, free-cutting brass, based on 100 percent for C 36000. [d] 29.4 kN (3000 kgf) load. [e] R_A, R_B, R_F, Rockwell numbers in A, B, F scales.

Note: Values tabulated are average values of test specimens.

Source: *ASM Metals Handbook*, American Society for Metals, Metals Park., Ohio, 1988.

TABLE 1-32
Nominal compositions and typical room-temperature mechanical properties of some magnesium alloys

Alloy	Composition: Al	Mn(a)	Th	Zn	Zr	Others	Tensile strength, σ_{st}: MPa	kpsi	Yield strength, σ_{sy}: Tensile: MPa	kpsi	Compressive: MPa	kpsi	Bearing: MPa	kpsi	Elongation in 50 mm (2 in), %	Shear strength, τ_s: MPa	kpsi	Brinell[b] hardness, H_B
Sand and Permanent Mold Castings																		
AZ63A–T6	6.0	0.15		3.0			275	40	130	19	130	19	360	52	5	145	21	73
AZ81A–T4	7.6	0.13		0.7			275	40	83	12	83	12	305	44	15	125	18	55
AZ92A–T6	9.0	0.10		2.0			275	40	150	22	150	22	450	65	3	150	22	84
HK3IA–T6			3.3		0.7		220	32	105	15	105	15	275	40	8	145	21	55
HZ32A–T5			3.3	2.1	0.7		185	27	90	13	90	13	255	37	4	140	20	57
ZE41A–T5				4.2	0.7	1.2 RE	205	30	140	20	140	20	350	51	3.5	160	23	62
ZH62A–T5			1.8	5.7	0.7		240	35	170	25	170	25	340	49	4	165	24	70
ZK61A–T6				6.0	0.7		310	45	195	28	195	28			10	180	26	70
Die Castings																		
AM60A–F	6.0	0.13					205	30	115	17	115	17			6			
AS41A–F[c]	4.3	0.35				1.0 Si	220	32	150	22	150	22			4			
AZ91A and B–F[c]	9.0	0.13	0.7				230	33	150	22	165	24			3	140	20	63
Extruded Bars and Shapes																		
AZ31B and C–F[d]	3.0			1.0			260	38	200	29	97	14	230	33	15	130	19	49
AZ80A–T5	8.5			0.5			380	55	275	40	240	35			7	165	24	82
HM31A–F		1.2	3.0				290	42	230	33	185	27	345	50	10	150	22	
ZK60A–T5				5.5	0.45[a]		365	53	305	44	250	36	405	59	11	180	26	88
Sheets and Plates																		
AZ3IB–H24	3.0			1.0			290	42	220	32	180	26	325	47	15	160	23	73
HK31A–H24			3.0		0.6		255	33	200	39	160	23	285	41	9	140	20	68
HM21A–T8		0.6	2.0				235	34	170	25	130	19	270	39	11	125	18	

[a] Minimum.
[b] 4.9-kN (500-kgf) load, 10-mm ball.
[c] A and B are identical except that 0.30% max residual Cu is allowable in AZ91B.
[d] Properties of B and C are identical, but AZ31C contains 0. 15 min Mn, 0.1 max Cu, and 0.03 max Ni.
Source: *ASM Metals Handbook*, American Society for Metals, Metals Park, Ohio, 1988.

TABLE 1-33
Mechanical properties[a] of some nickel alloys[4]

Name of alloy	Condition	Ultimate tensile strength, σ_{sut}		Tensile yield strength, σ_{syt} (0.2% offset)		Elongation in 50 mm (2 in), %	Hardness number	Impact strength notched Charpy		Typical uses
		MPa	kpsi	MPa	kpsi			J	ft-lbf	
Nickel 200	Bar, cold-drawn	448–758	65–110	276–690	40–100	35–10				Corrosion-resistant parts
	Annealed	379–517	55–75	103–207	15–30	35–40				
Nickel 270	Strip, cold-drawn	655	95	621	90	4	$95R_B$			
	Annealed	345	50	110	16	50	$35B_B$			
Durnickel 301	Bar, cold-drawn, annealed	620–825	90–120	205–415	30–60	55–35	$35R_C$			High strength and hardness, corrosion resistance
	Age-hardened	1275	185	910	132	28				
Monel 400	Bar, annealed, 21°C (70°F)	517–621	75–90	172–345	25–50	60–35				Corrosion-resistant parts
	Wire. annealed	483–655	70–95	205–380	30–50	45–25				
	Spring temper	1000–1240	145–180	862–1172	125–170	5–2				Springs
Monel K-500	Bar, drawn, age-hardened	965–1172	140–170	724–1034	105–150	30–20	$24R_C$	53	39	Corrosion-resistant parts
Inconel 600	Rod, annealed	624	91	210	30.4	49	$75R_B$			Jet engines, missiles, etc. where corrosion resistance and high strength are required
	As rolled	672	98	307	45	46	$86R_B$			
Inconel 825	Bar, annealed, 21°C (70°F)	1276	185	910	132	28				
	871°C (1600°F)	135	19.6	117	17.0	102				Superalloy, jet engine, turbine, furnace
Inconel X-750	Bar, 21°C (70°F)	1120	162	635	92	24				
	760°C (1400°F)	485	70	455	66	9				
Incoloy 800	Bar, annealed	512–690	75–100	207–414	30–60	60–30				
	Hot-finished	552–827	80–120	241–621	35–90	50–25				
	Wire, spring temper	965–1207	140–175	896–1172	130–170	5–2				
Hastelloy W	Bar, solution-treated	725	105	260	38	56.0				
	425°C (800° F)									
	900°C (1650°F)	352	52	220	32	14.5				
Hastelloy G-3	Sheet, 6.4–19 mm (0.25–0.75 in) thick	740	107	365	53	56	$87R_B$			
Hastelloy B	Bar, cast	924	134	462	67	52				
Udimet 700	Bar, 21°C (70°F)	1410	204	965	140	17				Jet engines, missiles, turbines where high-temperature strength and corrosion resistance are important
	870°C (1600°F)	690	100	635	92	27				
Unitemp AF2–IDA	Bar, 21°C (70°F)	1290	187	1050	152	10				
	870°C (1600°F)	830	120	715	104	8				
Rene 95	Bar, forging 21°C (70°F)	1620	235	1310	190	15				
	650°C (1200°F)	1460	212	1220	177	14				
Waspaloy	Bar, 21°C (70°F)	1280	185	795	115	25				
	870°C (1600°F)	525	76	515	75	35				

[a] Values shown represent usual ranges for common sections.
[b] Values tabulated are approximate average ones.
Source: *ASM Metals Handbook*, American Society for Metals, Metals Park, Ohio, 1988.

TABLE 1-34
Mechanical properties of some zinc casting alloys[8]

Designation of alloy				Ultimate tensile strength, σ_{sut}		Tensile yield strength, σ_{syt}		Brinell hardness, H_B	Elongation in 50 mm (2 in), %	Impact strength Charpy		Fatigue endurance limit, σ_{sf}, 10^8 cycles	
Grade	ASTM	SAE	UNS	MPa	kpsi	MPa	kpsi			J	ft-lbf	MPa	kpsi
						Die-Casting Alloys							
Alloy 3	AG 40 A	903	Z 33520	283	41			82	10	58	43	47	6.8
Alloy 5	AC 41 A	925[a]	Z 35531	324	47			91	7	65	48	56	8.2
Alloy 7		903		283	47				14	54	40		
						Zinc Foundry Alloys							
	ZA-12												
	Sand-cast			276–310	40–45	207	30	105–120	1–3				
	Permanent Mold			310–345	45–50	214	31	105–125	1–3				
	Die-cast			393	57	317	46	110–125	2				
	ZA-27												
	Sand-cast			400–440	58–64	365	53	110–120	3–6				
	Sand-cast			310–324	45–47	255	37	90–100	8–11				
	Die-cast			448	65	434	63	110–125	1				

[a] Die-cast.

Note: Values given are average values.

Source: *Machine Design*, 1981 Materials Reference Issue, Penton/IPC, Cleveland, Ohio, Vol. 53, No. 6 (March 19, 1981); *SAE Handbook*, pp. 11–123, 1981.

TABLE 1-35
Mechanical properties of some wrought titanium alloy[4]

Name of alloy	UNS no.	Designation	Ultimate tensile strength, σ_{sut} MPa	Ultimate tensile strength, σ_{sut} kpsi	Tensile yield strength, σ_{syt} MPa	Tensile yield strength, σ_{syt} kpsi	Elongation in 50 mm (2 in), %	Strength impact Charpy J	Strength impact Charpy ft-lbf	Hardness	Machi-nability	Uses
Commercially pure titanium	R 50520	ASTM Grade 1	240	35	170	25	24	35	26[a]		40[b]	Resistance to temperature effect of structures, easy to fabricate, excellent corrosive resistance, cyrogenic applications
Commercially pure titanium		ASTM Grade 2	340	50	280	40	22					
Commercially pure titanium		ASTM Grade 3 (Ti-65A)	450	65	380	55	20			$30R_C$		
Commercially pure titanium		ASTM Grade 4	550	80	480	70						
Alpha alloy	R 54520	Ti-5Al-2.5Sn	790	115	760	110						Gas turbine engine casting and rings, aerospace
Alpha alloy	R 54521	Ti-5Al-2.5Sn-ELI	690	100	620	90	19				30[b]	structural members, excellent weldability,
Alpha alloy	R 54790	Ti-2.25Al-11Sn-5Zr-IMo	1000	145	900	130						pressure vessels, excellent corrosive resistance, jet engine blades and wheels, large bulkhead forgings
Alpha-beta alloy	R 56400	Ti-6AI-4V[b]	900	130	830	120	10	24.5	18[e]	$34R_C$	22[b]	Most widely used alloy, aircraft gas turbine
		Ti-6Al-6V-2Sn	1030	150	970	140						disks and blades, turbine disks and blades,
		Ti-10V-2Fe-3Al[a,c]	1170	170	1100	160						air frame structural components, gas turbine
	R 56260	Ti-6A1-2Sn-4Zr-6Mo[e]	1170	170	1100	160						engines, disks and fan blade, components of compressors
Beta alloy	R 58010	Ti-13V-11Cr-3Al										Missile applications such as solid rocket motor
Beta alloy		Ti-3Al-8V-6Cr-4Mo-4Zr[b,c]	900	130	830	120	4	13.5	10		40[b]	cases, advanced manned and unmanned airborne systems, springs for airframe applications

[a] At 0.2% offset.
[b] Mechanical and other properties given for annealed conditions.
[c] Mechanical and other properties given for solution-treated and aged condition.
[d] Based on a rating of 100 for B1112 resulfurized steel.
[e] Approximate values of annealed bars at room temperature.
Source: *Metals Handbook*, Desk Edition, ASM International, Materials Park, Ohio 44073-0002, 1985 (formerly the American Society for Metals, Metals Park, Ohio, 1985).

TABLE 1-35A
Mechanical properties of powder metallurgy and wrought titanium and titanium-base alloys

Name of alloy	Processing	Density ρ, %	Ultimate tensile strength, σ_{sut} MPa	Ultimate tensile strength, σ_{sut} kpsi	Yield strength, σ_{sy} MPa	Yield strength, σ_{sy} kpsi	Fatigue limit notched, σ_{sf} MPa	Fatigue limit notched, σ_{sf} kpsi	Fracture toughness, K_{IC} MPA $\sqrt{m}$	Fracture toughness, K_{IC} kpsi $\sqrt{in}$	Elastic modulus, E GPa	Elastic modulus, E Mpsi	Elongation, %	Reduction in area, %
Wrought commercial purity		100	345	50	344	50					103	15	5	35
titanium Grade II		95.5	414	60	324	47					103	15	15	14
Sponge commercial purity[a]		94	427	62	338	49								
Powder metallurgy titanium	Forged	100	455	66	365	53							23	30
Wrought Ti-6Al-4V (AMS 4298)		100	896	130	827	120	427	62	55[e]	50[e]	114	16.5	10	20
Powder metallurgy Ti-6Al-4V	Blended elemental alloy, cold	95.5	876	127	786	114	193	28	45[e]	40[e]	117	17	8	14
	Blended elemental alloy, forged,	99 min	937	136	862	125	414	60	61[e]	56[e]	116	16.8	12–18	15-40
	preforms or vacuum hot pressed	99	1103	160	1013	147							4.9	7.6
	Solution treated and aged													
Plasma rotating electrode processed Ti-6Al-4V	Hot isostatically pressed	100	951	138	910	132	414[d]	60[d]	83[f]	76[f]			15	39
Powder metallurgy Ti-6Al-4V[a]		94	827	120	738	107							5	8
	Forged	100	920	133.5	841	122							11.5	25

[a] 0.12% oxygen.
[b] 0.2% oxygen.
[c] Consolidated at 811 MPa (58.8 tpsi), 0.5 s dwell in low-carbon steel fluid dies. Preheat temperature was 940°C (1725°F) held at temperature 0.75 h. Powder was vacuum filled into fluid dies following cold static outgassing for 24 h.
[d] $K_t = 3$.
[e] K_e.
[f] K_{tc}.
Source: *Metals Handbook*, Desk Edition, ASM International, Materials Park, Ohio 44073-0002, 1985 (formerly the American Society for Metals, Metals Park, Ohio, 1985).

TABLE 1-36
Mechanical properties of some lead alloys

UNS No.	Ultimate tensile strength, σ_{sut}		Yield strength, σ_{sy}		Shear strength, τ_s		Fatigue strength at 10^7 cycles, σ_{sf}		Hardness number, H_B	Elongation in 50 mm (2 in), %	Creep	Uses
	MPa	psi	MPa	psi	MPa	psi	MPa	psi				
50042	12-13	1740–1885	55	7978	12.5	1810	3.2	464	3.2–4.5	30		Low melting-point chemical process applications, used as solder for the jobs lead alloyed with tin, bismuth cadmium, indium forms alloys with low melting point. Some of these are fusible alloys, used in automotive devices, fire extinguishers, sprinkler heads.
50132	35	5076									19.5 MPa-1000 h	
	1.8 MPa at 100°C	261 at 212°F							13	28	7.5 MPa-1000 h at 100°C	
50750	70	10152	66	9570						10	28 MPa for 100 h	
51120	16-19	2320–2755	6–8	870–1160			4.3	624	4–6		3% per year at 2.07 MPa	
52901	27.6	4002					10.30	1495	8.1	48		
53620	71	10297					30 MPa at 2×10^7	4358 at 2×10^7	20	2		
54321	28	4060	10	1450					8	55		
54520	30	4350							10	10	3.5 MPa for 1000 h	
	8 MPa at 100°C								30% at 100°C		1.1 MPa for 1000 h at 100°C (212°F)	
54820	34	4930			28	4060			12	18	0.790 MPa for 0.01% per day	
54915	37	5367								25		
	6 MPa at 100°C	870			32	4640			12	130	2.1 MPa for 1000 h	Wiping solder for joining lead pipes and cable sheaths; for automobile radiator cores and heating units
55030	32.4	4700	33	4790	36	5200			14	60		For general purpose; most popular of all lead alloys
55111	52.5	7610								30–60	2.9 MPa for 1000 h	
	19 MPa at 100°C	2756			37	5380			16	135–200 at 100°C (212°F)	0.45 MPa for 1000 h at 100°C (212°F)	

Note: Values tabulated are average values obtained from standard test specimens.
Source: *Metals Handbook*, Desk Edition, ASM International, Materials Park, Ohio 44073-0002, 1985 (formerly the American Society for Metals, Metals Park, Ohio, 1985).

TABLE 1-37
Mechanical properties of bronzes

Property	Mode of casting test pieces	Railway, bronze					Aluminum bronze			Tin bronze	Silicon bronze
		Class I phosphor[a] bronze [b]	Class II gun metal[c]	Class III leaded	Class IV bronze[d]	Class V leaded[e] gun metal	Grade I	Grade II	Grade III		
Ultimate strength, min σ_{sut}, MPa (kpsi)	Sand-cast (cast-on)	186 (27.0)[f]	196 (28.4)	137 (19.9)	157 (22.8)	186 (27.0)				216 (31.3)	
	Sand-cast (separately cast)	206 (29.9)[f]	216 (31.3)	157 (22.8)	176 (25.5)	206 (29.9)	647 (93.8)	490 (71.0)	446 (64.7)	226 (32.8)	309 (44.8)
	Chill-cast						647 (93.8)	539 (78.2)	196 (28.4)	245 (35.5)	
Elongation percent, min	Sand-cast (cast-on)	3.0	8.0	2.0	2.0	8.0				8.0	
	Sand-cast (separately cast)	5.0	12.0	4.0	4.0	12.0	15.0	20.0	20.0	12.0	20.0
	Chill-cast						12.0	20.0			

[a] Brinell hardness, H_B for phosphor bronzes: 60 for sand cast (cast-on) test pieces and 65 for sand-cast (separately cast) test pieces.
[b] Used for locomotive side valves, oil-lubricated side rod, pony pivot bushes, steel axle box, oil-lubricated connecting rod.
[c] Used for fusible plugs, relief valves, whistle valve body, stuffing box, nonferrous boxes, oil-lubricated connecting rod, large end bearings.
[d] Used for locomotive grease lubricated non-ferrous axle boxes, side rod and motion bushes.
[e] Used for castings for carriage and wagon bearings shells.
[f] σ_{sut} given in parentheses are the units in US Customary Units (kpsi).

TABLE 1-38
Mechanical properties of rubber and rubber-like materials

Material	Specific gravity	Compressive strength, σ_{sc}		Tensile strength, σ_{st}		Transverse strength, σ_{sb}		Hardness shore durometer	Maximum temperature			Effect of heat
		MPa	kpsi	MPa	kpsi	MPa	kpsi		K	°C	°F	
Duprene	1.27–3.00			1.4–28	0.2–4.0			15–95	422	149	300	Stiffens slightly
Koroseal (hard)	1.30–1.40			14–62	2.0–9.0			80–100	373	100	212	Softens
Koroseal (soft)	1.20–1.30			3.4–17	0.6–2.6			30–80	361	88	190	Softens
Plioform (plastic)	1.06	88	12.8	28–34	4.0–5.0	48	7.0		344–393	71–120	160–250	
Rubber[b] (hard)	1.12–2.00	758	110.0	7–69	1.0–10.0	62	9.0	50[a]/80	328–367	55–71	130–160	Softens
Rubber[c] (soft)	0.97–1.25	14	2.0	3.5	0.6	62	9.0		339–367	65–94	150–200	Softens
Rubber (linings)	0.98–1.35	103	15.1			103	15.1		361	88	190	Softens

[a] Sclerscope.
[b] Coefficient of linear expansion from 0 to 333 K (60°C = 140°F) is 35×10^{-6}.
[c] Coefficient of linear expansion from 0 to 333 K (60°C = 140°F) is 36×10^{-6}.

TABLE 1-39
Properties of some thermoplastics

Name of plastic	Tensile strength, σ_{sut}		Elongation in 50 mm (2 in), %	Modulus of elasticity, E		Izod impact strength		Hardness, Rockwell	Resistance to		Coefficient of friction, μ		Application
	MPa	kpsi		GPa	Mpsi	J	ft-lbf		Heat	Chemical	With plastic	With steel	
ABS (general purpose	41	6	5–20	2.3	0.33	8.8	6.5	103	Available	Fair			Light-duty mechanical and decorative eyeglass frames, automobile-steering wheels, knobs, handles, camera cases, battery cases, phone and flashlight cases, helmets, housing for power tools, pumps
Acrylics	37–72	5.4–10.5	5–50	1.5–3.1	0.22–0.45	0.5–1.6	0.4–1.2	92–100 M	Available	Fair			Light-duty mechanical knobs, pipe fittings, automobile-steering wheels, eyeglass frames, tool handles, camera cases, optical and transparent parts for safety glasses, snowmobile windshields, refrigerator shelves
Acetal	55–69	8–10	40–60	2.8–3.6	0.4–0.52			80–94 M	Good	High			Mechanical gears, cams, pistons, rollers, valves, fan blades, washing-machine agitators, bushings, bearings, chute liners, wear strips, and structural components
Cellulosic (cellulose acetate)	15.2–47.5	2.2–6.9		0.5–2.8	0.065–0.40	1.4–9.9	1.0–7.3	122 R					Decorative knobs, handles, camera cases, pipes, pipe fittings, eyeglass frames, phone and flashlight cases, helmets, pumps and power tool housings, transparent parts for safety glasses, lens signs, refrigerator shelves and snowmobile windshields, extruded and cast film, and sheet for packaging
Epoxy resin (glass-fiber filler)	69–138	10–20	4.0	21.0	3.04	2.7–41	2–30	100–110 M					Filament wound structures, aircraft pressure bottles, oil storage tanks and high-performance tubing, reinforced glass-fiber composites
Fluoroplastic group	3–48	0.5–7.0	100–300			4.1	3	50-80 D	Excellent	Excellent		0.05	Gears, bearings, tracks, bushings, roller-skate wheels, chute liners
Nylon	55–83	8–12	60–200	1.2–2.9	0.18–0.42	1.4–4.5	1.0–3.3	114–120 R	Poor	Good	0.04-0.13		Structural, mechanical components such as gears, fan blades, washing-machine agitator, valve, pump, impeller, pistons, and cams
Phenolic (general purpose)	45–48	6.5–7.0		7.6–9.0	1.1–1.3	0.4–0.5	0.30–0.35	70–95 E					Wall plates, industrial switch gears, handles for appliances, housing for vacuum cleaners, automatic transparent rings, housing for thermostats, small motors, small tools, communication instruments, components for aircraft and computers, used as synthetic rubber for tires

TABLE 1-39
Properties of some thermoplastics (*Cont.*)

Name of plastic	Tensile strength, σ_{sut}		Elongation in 50 mm (2 in), %	Modulus of elasticity, E		Izod impact strength		Hardness, Rockwell	Resistance to		Coefficient of friction, μ		Application
	MPa	kpsi		GPa	Mpsi	J	ft-lbf		Heat	Chemical	With plastic	With steel	
Phenylene oxide	48-123	7.0-17.3	4–60	2.4–6.4	0.35-0.93	2.7-6.8	2-5	115-119 R 106-108 L	Good	Fair			Small housing for power tools, pumps, small appliances, hollow shapes for telephones, flashlight cases, helmets, TV cabinets, cable protective cover, bush-bar sleeves, scrubber-vane mist eliminators
Polycarborate	55-110	8-16	10-125	2.3-5.9	0.34-0.86	2.7-21.7	2-16	62- 91 M	Excellent	Fair	0.52	0.39	Mechanical gears, pistons, rollers, pump impellers, fan blades, rotor housing for pumps, power tools, phone cases, transparent parts for safety glasses, lenses and snowmobile windshields, refrigerator shelves, and flashlight cases
Polyimide	25–345	3.6–50	<1			0.3–23	0.25–17	88–120 M	Excellent	Excellent			Molded polyimides are used in jet-engine vane bushings, high load bearings for business machines and computer printout terminals, gear pump gaskets, hydraulic valve seals, multilayer printed-circuit boards, tubes for oil-well exploration
Polyester	55–159	8–23	1–300	1.9–11.7	0.28–1.7	0.7–2.6	0.5–1.9	65–100 M	Excellent	Poor	0.12 0.22	0.12 0.13	Flashlight and phone cases, housing for pumps, power tools and other appliances, gears, bushings, bearings, tracks, roller-skate wheels and chute liners
Polyethylene	4–38	0.6–5.5	20–1000	0.1–1.2	0.014–0.18	0.7–27.1	0.5–20	10–65 *R*					Decorative knobs, automobile steering wheels, eyeglass frames, tool handles, camera cases, phone and flashlight cases, housings for pump and power tools
Polypropylene	34–100	5–14.5	10–500	0.7–6.2	0.1–0.9	0.7–3.0	0.5–2.2	50–110 *R*					Mechanical cams, pistons, washing machine agitators, fan blades, valves, pump impellers, gears, bushings, chute liners, bearings, tracks, wear strips and other wear-resisting parts
Polysulfone	70	10.2	50–100	25	0.36	1.8	1.3	120 *R*	Excellent	Excellent			Pipe fittings, battery cases, knobs, camera and handle cases, trim moldings, eyeglass frames, tool handles, housings for pumps, power tools, phone cases, transparent parts, safety glasses, lenses, snowmobile windshields, signs, refrigerator shelves, and vandal-resistant glazing

Source: *Machine Design*, 1981 Materials Reference Issue, Penton/IPC, Cleveland, Ohio. Vol. 53, No. 6 (March 19, 1981).

TABLE 1-40
Properties of some thermosets[8]

	Tensile strength, σ_{st}		Modulus of elasticity, E		Hardness, Rockwell	Elongation in 50 mm (2 in), %	Impact strength Izod		Resistance		Application
Name	MPa	kpsi	GPa	Mpsi			J	ft-lbf	Heat	Chemical	
Alkyd	21–66	3–9.5	2–21	0.3–3.0	98E–99 M		0.5–14	0.3–10	Good	Fair	Military switch gear, electrical terminal strips, and relay housings and bases, automotive ignition parts, radio and TV components, switch gear, and small-appliance housings
Allylic	28–69	4–10			103–120 M		0.3–16	0.2–12	Excellent	Excellent	Switch gear and TV components, insulators, circuit boards, and housings, tubing and aircraft parts, copper-clad laminate for high-performance printed-circuit boards
Amino	34–69	5–1 0	9–16	1.3–2.4	110–120 M	0.3–0.9	0.4–24	0.27–18	Excellent	Excellent	Electrical wiring devices and switch housings, toaster and other appliance bases, push buttons, knobs, piano keys and camera parts, dinnerware, utensil handles, food-service trays, housings for electric shavers and mixers, metal blocks, connector plugs, automotive and aircraft ignition parts, coil forms, used as baking enamel coatings, particle-board binders, paper and textile treatment materials
Epoxy	28–138	4–20	2.5–21	0.35–3.04	80–120 M	1–10	0.3–41	0.2–30	Excellent	Excellent	Filament wound structures, aircraft pressure bottles, oil storage tank, used with various reinforcements, glass fibers, asbestos, cotton, synthetic fibers, and metallic foils, imprinted circuits, graphite and carbon-fiber-reinforced laminates used for radomes, pressure vessels, and aircraft components requiring high modulus and light weight, potting and encapsulating electrical and electronic components ranging from miniature coils and switches to large motors and generators
Phenolics	34–62	5–9	7–17	1.0–2.5	70–95 E		0.4–1.5	0.26–1.05	Excellent	Good	Handles for appliances, automotive power-brake systems and industrial terminal strips, industrial switch gear, housing for vacuum cleaners, handles for pots and pans, automotive transmission rings, and electrical components, thermostat housings, housing for small motors and heavy-duty electrical components, small power tools, electrical components for aircraft and computers, pump housings, synthetic rubber for tires and other mechanical rubber goods, dry ingredients for brake linings, clutch facings and other friction products
Silicone	3–45	0.4–6.5			80–90 M	15	0.5–14	0.3–10	Excellent	Excellent	Refrigerator equipment, used as a washing, sealant, laminating parts, injection mold silicon rubber

Source: *Machine Design*, 1981 Materials Reference Issue, Penton/IPC, Cleveland, Ohio. Vol. 53, No. 6 (March 19, 1981).

TABLE 1-41
Optical and mechanical properties of photoelastic material[6]

	Elastic limit, σ_{se}		Tensile strength, σ_{st}		Young's modulus, E			Stress fringe value, f_σ		Strain fringe value, f_s		Figure of merit, $Q = (E/f_\sigma)$		$S = \sigma_e/f\sigma$		
Material	**MPa**	**kpsi**	**MPa**	**kpsi**	**GPa**	**kpsi**	**Poisson's ratio, ν**	**kN/m fri**	**lbf/in fri**	**µm/fri**	**µin/fri**	**fri/m**	**fri/in**	**fri/m**	**fri/in**	**Remarks**
Glass	60.0	8.68	69.0	10.0	69.0	10,000	0.20	304.724– 423.812	1740–2420	4.83	191	226,000– 163,000	5747–4132	1970–1415	5–3.5	Low optical sensitivity; rarely used
Cataline (61-893)	38.0–62.0	5.55–9.0	88.2–117.2	12.5–17.0	4.2–4.3	615.0–628.0	0.365	15.236	87	4.83	191	27,600– 280,000	7069–7218	2500–4070	63.8–100	Used for 2-dimensional (2-D) and 3-dimensional (3-D) models; susceptible for time edge effect
Methyl methacrylate (unplasticized)			48.2	7.0	2.8	400.0	0.38	154,113	880	91.00	3582	18,200	455			
Polystyrene								54.290	310							Low optical sensitivity
Cellulose nitrate	27.6	4.0	51.7	7.55	2.4	350.0	0.33	42.907	245	25.40	1000	56,000	1428	643	16.3	Free from time edge effect; used
Castolite					4.3	623.0	0.35	31.873	182	1.00	39	135,000	3423			for photoplasticity
Kriston			56.5	8.25	3.7	540.0		14.010	80	4.83	191	264,000	6750			
CR-39 (Columbia resin)	20.6	3.0	48.0–41.4	7.0–6.0	1.7–2.6	250.0–380.0	0.42	14.623–17.338	83.5—99	11.90–12.50	468–492	116,000– 150,000	2994–3838	1408–1188	36.0–30.0	Used for 2-D models; free from time edge effect
Epoxy Resin:																
Araldite CN-501	28.3 at 299 K	4.12 at 77°F			3.10 at 298 K	452.0 at 77°F		10.770 at 298 K	61.5 at 77°F	4.57 at 298 K	180 at 77°F	290,000	7350	2628	67	Used for 2-D and 3-D models
Araldite 6020 at 299.7 K (80°F)					3.10	445.0	0.35	10.157	58.0	4.57	180	305,000	7672			Used most commonly for 2-D and 3-D models
Araldite 6020 at 277.4 K (40°F)								10.595	60,5							Used for 2-D and 3-D models
Araldite B			68.9	10.0	3.2 at 294 K	460 at 70°F	0.362	10.332	59.0	4.83	191	310,000	7796			Used most commonly for 2-D and 3-D models
Bakelite ERL 2774 (50 phthalic anhydride)	55.2	8.0			3.30 0.036 at 433 K	478.5 5.2 at 320°F	0.38	10.30 0.435 at 433 K	58.75 2.5 at 320°F	4.3	170	320,000 83,000	8145 2080	5360	136	Used for 2-D and 3-D models
Hysole 4290:																
at 296.9 K (75°F)	48.3	7.0	82.7	12.0	3.45	500.0	0.34	10.508	60.0			328,000	8333	4596	16	Used for 2-D and 3-D models
at 405.2 K (270°F)			1.38	0.20	0.014	2.0	0.50	0.245	1.4			57,000	1428			
Armstrong C-6	22.4 at 296.3 K	3.25 at 74°F			3.3 at 294 K	475 at 70°F		13.222 at 293.6 K	75.5 at 70°F	5.59 at 293.6 K	220 at 70°F	290,000	6291	1694	43	Used for 2-D and 3-D models
Polycarbonate	34.5	5.0			2.55	370.0	0.38	7.355	42.0	4.00	157	347,000	8810	4690	119	Little optical and mechanical creep
Marblette [annealed 72 h at 356 K (181°F)]					3.79 –4.13	550.0 – 600.0	0.41	14.535	83.0	5.33	210	261,000	6626			Good stress-optical relationship; susceptible for time edge effect

TABLE 1-41
Optical and mechanical properties of photoelastic material (*Cont.*)

Material	Elastic limit, σ_{se}		Tensile strength, σ_{st}		Young's modulus, E		Poisson's ratio, ν	Stress fringe value, f_σ		Strain fringe value, f_s		Figure of merit, $Q = (E/f_\sigma)$		$S = \sigma_e/f\sigma$		Remarks
	MPa	kpsi	MPa	kpsi	GPa	kpsi		kN/m fri	lbf/in fri	µm/fri	µin/fri	fri/m	fri/in	fri/m	fri/in	
Marblette (phenofomaldehyde)	18.9	2.70	31.0	4.50	1.65	240.0	0.40	9.982	57.0	7.87	310	165,000	4210	893	47.4	Good stress-optical relationship;
Catalin 800	6.9	1.0	46.2	6.70	1.72	250.0	0.38	10.087	57.6	5.84	230	170,000	4340	684	17.4	susceptible for time edge effect
Natural rubber																
Hard								1.752	10.0							
Soft								0.289	1.7	431.80	17000					
Urethane rubber																
Hysole 8705 at 26.9 K (75°F)					0.003	0.425	0.467	0.084	0.5	40.60	1598	35,700	850			Used for preparation of models in stress wave propagation and models of dam
Hysole 4485	0.17	2.85 $\times 10^{-2}$			0.003–0.004	0.425–0.625	0.46	0.158	0.9	82.00	3228	19,000–25,000	4722–694	1076	31.6	
Gelatin (15% gelatin, 25% glycerine, 60%water)					75.8 $\times 10^{-6}$	11 $\times 10^{-3}$	0.50	0.025	0.14	483.00	19016	3032	78			Great optical sensitivity; used for model study of body forces

Sources: K. Lingaiah, *Machine Design Data Handbook*, Vol. II (*SI and Customary Metric Units*), Suma Publishers, Bangalore, India, 1986, and K. Lingaiah and B. R. Narayana Iyengar, *Machine Design Data Handbook*, Vol. I (*SI and Customary Metric Units*), Suma Publishers, Bangalore, India, 1986.

TABLE 1-42
Typical mechanical properties of commercial machinable tungsten alloys

		Density, ρ		Ultimate tensile strength, σ_{sut}		Yield[a] strength, σ_{spl}		Proportional limit, σ_{spl}		Modulus of elasticity, E				Coefficient of thermal expansion, α			
Class	Classification of alloy	Mg/m^3	lb/in^3	MPa	kpsi	MPa	kpsi	MPa	kpsi	GPa	Mpsi	Elongation in 50 mm (2 in), %	Hardness	μm/m°C	μin/in°F	Magnetic properties	Tungsten, % by weight
1	W-Ni-Cu alloy	17.0	0.614	785	114	605	88	205	30	275	40	4	27 R_C	5.4	3.0	Virtually nonmagnetic	Class 1, 89–91
2	W-Ni-Fe alloy	17.0	0.614	895	130	615	89	260	38	275	40	16	27 R_C	5.4	3.0	Slightly magnetic	Class 2, 91–94
3	W-Ni Fe alloy	18.0	0.650	925	134	655	95	350	51	310	45	6	29 R_C	5.3	2.9	Slightly magnetic	Class 3, 94–96
4	W-Ni-Fe alloy	18.5	0.667	795	115	690	100	450	65	345	50	3	32 R_C	5.0	2.6	Slightly magnetic	Class 4, 96–98

[a] 0.2% offset; R_C, Rockwell hardness scale C.

Source: *Metals Handbook* Desk Edition, ASM International, Materials Park, OH 44073-0002 (formerly The American Society for Metals, Metals Park, OH 44073), 1985.

TABLE 1-43
Representative properties for fiber reinforcement

	Typical fiber diameter		Density, ρ		Tensile strength, σ_{st}		Modulus of elasticity, E		Coefficient of thermal expansion, α		Thermal conductivity, K	
Fiber	$\times 10^{-3}$ mm	$\times 10^{-3}$ in	g/cm^3	lb/in^3	MPa	kpsi	GPa	Mpsi	μm/mK	μin/in°F	$W/(m^2K/m)$	$Btu/(ft^2h°F)/in$
E glass	10.2	0.4	2.48	0.092	3100	450	72.5	10.5	5.0	2.8	1680	7.5
S glass	10.2	0.4	2.43	0.090	4498	650	85	12.3				
970 S glass	10.2	0.4	2.46	0.091	5510	800	100	14.5				
Boron on tungsten	102.0	4	2.56	0.095	2756	400	415	60	5.0	2.8		
Graphite	5–10	0.2–0.4	1.43–1.75	0.053–0.066	1723–3445	250–500	241–689	35–100	2.7	1.5	13440	60
Beryllium	127	5	1.78	0.066	1240	180	310	45	11.5	6.4	19488	87
Silicon carbide on tungsten	102	4	3.40	0.126	2480	360	414	60	4.0	2.2	6496	29
Stainless steel	13	0.5	7.64	0.283	2852–4184	385–600	200	29	54	30	22400–38080	100–170
Asbestos	0.025–0.25	0.001–0.01	2.43	0.090	689–2067	100–300	172	25				
Aluminum	5	0.2	2.62	0.097	1378–2067	200–300	138–413	20–60	6.5	3.7		
Polyamide	5–13	0.2–0.5	1.11	0.041	827	120	2.8	0.4	81–90	45–50	381	1.7
Polyester	20.5	0.8	1.49	0.052	690	100	4	0.6	81–90	45–50	381	1.7

Courtesy: J. E. Ashton, J. C. Halpin, and P. H. Petit, *Primer on Composite Materials—Analysis*, Technomic Publishing Co., Inc., 750 Summer Street, Stanford, Conn. 06901, 1969.

TABLE 1-44
Designation, composition and mechanical properties of ferrous powder metallurgy structural steels

MPIF material designation[a]	MPIF chemical composition limits and ranges[b], % Fe	C	Cu	Ni	MPIF density, ρ, g/cm^3	Condition[c]	Tensile strength, σ_{st} MPa	kpsi	Yield strength, σ_{sy} MPa	kpsi	Fatigue strength, σ_{sf} MPa	kpsi	Modulus of elasticity, E GPa	Mpsi	Impact energy J	ft-lbf	Elongation in 25 mm (1 in), %	Apparent hardness	ASTM designation
Iron and Carbon Steel																			
F-0000	97.7–100	0.3 max			<6.0	AS	110	10	75	11	40	6	70	10.5	4.1	3	2	10R_H	B 310, Class A
F-0000	97.7–100	0.3 max			6.8–7.2	AS	205	30	150	22	80	11[d]	130	19	20	15	9	15R_B	
F-0000	97.7–100	0.3 max			7.2–7.6	AS	275	40	180	26	105	15[d]	160	23	34	25	15	30R_B	
Steel																			
F-0005	97.4–99.7	0.3–0.6			6.0–6.4	AS	170	25	140	20	65	10[d]	90	13	4.7	3.5	1.5	20R_B	B 310, Class B
F-0005	97.4–99.7	0.3–0.6			6.4–6.8	AS	220	32	160	23	85	12[d]	110	16	6.8	5.0	2.5	45R_B	
F-0005	97.4–99.7	0.3–0.6			6.4–6.8	HT	415	60	395	57	155	23[d]	110	16	–	–	0.5	100R_B	
F-0008	97.0–99.1	0.6–1.0			6.0–6.4	AS	240	35	205	30	90	13[d]	90	13	4.1	3.0	1.0	50R_B	B 310, Class C
F-0008	97.0–99.1	0.6–1.0			6.0–6.4	HT	400	58	–	–	150	22[d]	90	13	–	–	<0.5	100R_B	
F-0008	97.0–99.1	0.6–1.0			6.4–6.8	AS	290	42	250	36	100	14[d]	110	16	4.7	3.5	1.5	65R_B	
F-0008	97.0–99.1	0.6–1.0			6.4–6.8	HT	510	74	–	–	195	28[d]	110	16	–	–	<0.5	25R_C	
F-0008	97.0–99.1	0.6–1.0			6.8–7.2	AS	395	57	275	40	150	22[d]	130	19	9.5	7.0	2.5	75R_B	
F-0008	97.0–99.1	0.6–1.0			6.8–7.2	HT	650	94	625	91	245	36[d]	130	19	–	–	<0.5	30R_C	
Iron Copper Steel																			
FC-0200	93.8–98.5	0.3 max	1.5–3.9		<6.0	AS	160	23	115	17	60	9[d]	90	13	7.5	5.5	2.5	80R_H	
FC-0200	93.8–98.5	0.3 max	1.5–3.9		6.8–7.2	AS	255	37	160	23	95	14[d]	130	19	23	17	7	30R_B	
Copper Steel																			
FC-0205	93.5–98.2	0.3–0.6	1.5–3.9		6.4–6.8	AS	345	50	260	38	130	19[d]	110	16	7.5	5.5	1.5	60R_B	
FC-0205	93.5–98.2	0.3–0.6	1.5–3.9		6.4–6.8	HT	585	85	560	81	220	31[d]	110	16	–	–	<0.5	30R_C	
FC-0205	93.5–98.2	0.3–0.6	1.5–3.9		6.8–7.2	AS	425	62	310	45	160	24[d]	130	19	13	9.5	3.0	75R_B	
FC-0205	93.5–98.2	0.3–0.6	1.5–3.9		6.8–7.2	HT	690	100	655	95	260	38[d]	130	19	–	–	<0.5	35R_C	
FC-0208	93.1–97.9	0.6–1.0	1.5–3.9		<6.0	AS	225	33	205	30	85	13[d]	70	10.5	3.4	2.5	<0.5	45R_B	B 426. Grade 1
PC-0208	93.1–97.9	0.6–1.0	1.5–3.9		<6.0	HT	295	43	–	–	110	16[d]	70	10.5	–	–	<0.5	95R_B	
FC-0208	93.1–97.9	0.6–10	1.5–3.9		6.4–6.8	AS	415	60	330	48	155	23[d]	110	16	6.8	5.0	1.0	70R_B	
FC-0208	93.1–97.9	0.6–1.0	1.5–3.9		6.4–6.8	HT	550	80	–	–	210	30[d]	110	16	–	–	<0.5	35R_C	
FC-0208	93.1–97.0	0.6–1.0	1.5–3.9		6.8–7.2	AS	550	80	395	57	210	30[d]	130	19	11	8.0	1.5	80R_B	
FC-0208	93.1–97.9	0.6–1.0	1.5–3.9		6.8–7.2	HT	690	100	655	95	260	38[d]	130	19	–	–	<0.5	40R_C	
FC-0505	91.4–95.7	0.3–0.6	4.0–6.0		6.0–6.4	AS	345	50	290	42	130	19[d]	90	13	6.1	4.5	1.0	60R_B	
					6.4–6.8	AS	455	66	380	55	170	25[d]	116	16	6.8	5.0	1.5	75R_B	
FC-0508	91.0–95.4	0.6–1.0	4.0–6.0		6.0–6.4	AS	425	62	395	57	160	24[d]	90	13	4.7	3.5	1.0	65R_B	B 426, Grade 2
					6.0–6.4	HT	480	70	480	70	185	27[d]	90	13	–	–	<0.5	30R_C	
FC-0508	91.0–95.4	0.6–1.0	4.0–6.0		6.4–6.8	AS	515	75	480	70	195	29[d]	116	16	6.1	4.5	1.0	85R_B	
FC-0808	86.0–93.4	0.6–1.0	6.0–11.0		<6.0	AS	250	36	–	–	–	–	–	–	–	–	<0.5	55R_B	B 426, Grade 3

TABLE 1-44
Designation, composition and mechanical properties of ferrous powder metallurgy structural steels (*Cont.*)

MPIF material designation[a]	MPIF chemical composition limits and ranges[b], %				MPIF density, ρ, g/cm^3	Condition[c]	Tensile strength, σ_{st}		Yield strength, σ_{sy}		Fatigue strength, σ_{sf}		Modulus of elasticity, E		Impact energy		Elongation in 25 mm (1 in), %	Apparent hardness	ASTM designation
	Fe	C	Cu	Ni			MPa	kpsi	MPa	kpsi	MPa	kpsi	GPa	Mpsi	J	ft-lbf			
Iron Copper																			
FC-1000	87.2–90.5	0.3 max	9.5–10.5		<60	AS	205	30	–	–	–	–	–	–	–	–	0.5	$70R_F$	B 222, B439, Grade 3
Iron Nickel																			
FN-0200	92.2–99.0	0.3 max	2.5 max	1.0–3.0	6.4–6.8	AS	195	28	125	18	75	11	115	17	19	14	4	$38R_B$	B 484, Grade 1, Class A
FN-0200	92.2–99.0	0.3 max	2.5 max	1.0–3.0	7.2–7.6	AS	310	45	205	30	125	18	160	23	36	50	11	$51R_B$	
Nickel Steel																			
FN-0205	91.9–98.7	0.3–0.6	2.5 max	1.0–3.0	6.4–6.8	AS	255	37	160	23	105	15	115	17	14	10	3.0	$50R_B$	B 484, Grade 1, Class B
						HT	565	82	450	65	225	33	115	17	8.1	6	0.5	$32R_C$	
FN-0205	91.9–98.7	0.3–0–6	2.5 max	1.0–3.0	6.8–7.2	SS	345	50	215	31	140	20	145	21	24	18	3.5	$70R_B$	
						HT	760	110	605	88	305	44	145	21	22	16	1.0	$42R_C$	
FN-0208	91.9–98.7	0.3–0.6	2.5 max	1.0–3.0	6.4–6.8	AS	330	48	205	30	130	19	115	17	11	8	2.0	$62R_B$	B 484, Grade 1, Class C
						HT	690	100	650	94	275	40	115	17	8.1	6	0.5	$34R_C$	
FN-0208	91.6–98.7	0.6–0.9	2.5 max	1.0–3.0	7.2–7.6	AS	545	79	345	50	220	32	160	23	30	22	3.5	$87R_B$	
						HT	1105	160	1070	155	415	60	160	23	24	18	0.5	$47R_C$	
Iron Nickel																			
FN-0400	90.2–97.0	0.3 max	2.0 max	3.0–5.5	6.8–7.2.	AS	340	49	205	30	140	20	145	21	47	35	6	$60R_B$	B 484, Grade 2, Class A
FN-0400					7.2–7.6	AS	400	58	250	36	160	23	160	23	68	50	6.5	$67R_B$	
Nickel Steel																			
FN-0405	89.9–96.7	0.3–0.6	2.0 max	3.0–5.5	6.4–6.8	AS	310	45	180	26	125	18	115	17	14	10	3.0	$63R_B$	B 484, Grade 2, Class B
FN-0405	89.9–96.7	0.3–0.6	2.0 max	3.0–5.5	6.4–6.8	HT	770	112	650	94	310	45	115	17	8.1	6	0.5	$27R_C$	
FN-0405					7.2–7.6	AS	510	74	295	43	205	30	160	23	41	30	6.0	$80R_B$	
FN-0405					7.2–7.6	HT	1240	80	1060	154	450	65	160	23	19	14	1.5	$44R_C$	
FN-0408	89.6–96.4	0.6–0.9	2.0 max	3.0–5.5	6.4–6.8	AS	395	57	290	42	160	23	115	17	81	6	1.5	$72R_B$	B 484, Grade 2, Class C
					7.2–7.6	AS	640	93	470	68	255	37	160	23	22	16	4.5	$95R_B$	
Iron Nickel																			
FN-0700	87.7–94.0	0.3 max	2.0 max	6.0–8.0	6.8–7.2	AS	490	71	275	40	195	28	145	21	28	21	4	$72R_B$	B 484, Grade 3, Class A
FN-0700						AS	585	85	330	48	240	34	160	23	35	26	6	$83R_B$	
Nickel Steel																			
FN-0705	87.4–93.7	0.3–0.6	2.0 max	6.0–8.0	6.4–6.8	AS	370	54	240	35	150	22	115	17	12	9	2.0	$69R_B$	B 484, Grade 3, Class B
						HT	705	102	550	80	280	41	115	17	11	8	0.5	$24R_C$	
FN-0705	–				7.2–7.6	AS	620	90	390	57	250	36	160	23	33	24	5.0	$90R_B$	
						HT	1160	168	895	130	500	65	160	23	27	20	1.5	$40R_C$	
FN-0708(e)	87.1–93.4	0.6–0.9	2.0 max	6.0–8.0	6.8–7.2	AS	550	80	380	55	220	32	145	21	16	12	2.5	$88R_B$	B 484, Grade 3, Class C
					7.2–7.6	AS	655	95	455	60	260	38	160	23	22	16	3.0	$96R_B$	

TABLE 1-44
Designation, composition and mechanical properties of ferrous powder metallurgy structural steels (*Cont.*)

MPIF material designation[a]	MPIF chemical composition limits and ranges[b], %				MPIF density, ρ, g/cm^3	Condition[c]	Tensile strength, σ_{st}		Yield strength, σ_{sy}		Fatigue strength, σ_{sf}		Modulus of elasticity, E		Impact energy		Elongation in 25 mm (1 in), %	Apparent hardness	ASTM designation
	Fe	C	Cu	Ni			MPa	kpsi	MPa	kpsi	MPa	kpsi	GPa	Mpsi	J	ft-lbf			
									Infiltered Steel										
FX-1005 (e)	80.5–91.7	0.3–0.6	8.0–14.9	–	7.2–7.6	AS	570	83	440	64	–	–	135	20	19	14	4.0	75R_B	
						HT	830	120	740	107	–	–	135	20	9.5	7.0	1.0	35R_C	
FX-1008 (e)	80.1–91.4	0.6–1.0	8.0–14.9	–	7.2–7.6	AS	620	90	515	75	–	–	135	20	16.0	12	2.6	80R_B	
						HT	895	130	775	105	–	–	135	20	9.5	7.0	60.5	40R_C	
FX-2000 (e)	70.7–85.0	0.3 max	15.0–25.0	–	7.2–7.6	AS	450	65	–	–	–	–	–	–	20	15	1.0	60R_B	B 303, Class A
FX-2005 (e)	70.4–84.7	0.3–0.7	15.0–25.0	–	–	AS	515	75	345	50	–	–	125	18	12.9	9.5	1.5	75R_B	B 303, Class B
						HT	790	115	655	95	–	–	125	18	8.1	6.0	<0.5	30R_C	
FX-2008 (e)	70.0–84.4	0.6–1.0	15.0–25.0	–	7.2–7.6	AS	585	85	515	75	–	–	125	18	14	10	1.0	80R_B	B 303, Class C
						HT	860	125	740	107	–	–	125	18	6.8	5.0	<0.5	92R_C	

[a] Designation listed are nearest comparable designations, ranges and limits may vary slightly between comparable designations.
[b] Metal Powder Industries Federation (MPIF) standards require that the total amount of all other elements be less then 2.0%, except that the total amount of other elements must be less than 4.0% infiltered steel.
[c] AS, as sintered; SS, sintered and sized; HT, heat treated, typically austenized at 870°C (1600°F), oil quenched and tempered at 200°C (400°F).
[d] Estimated as 38% of tensile strength.
[e] x indicates infiltered steel;
[f] Unnotched Charpy test; R_B = hardness Rockwell B scale; R_C = hardness Rockwell scale C; R_F = hardness Rockwell F scale.
Source: *Metals Handbook* Desk Edition, ASM International, 1985, Materials Park, OH 44073-0002 (formerly The American Society for Metals, Metals Park, OH 44073, 1985).

TABLE 1-45
Nominal composition of some of structural alloys at subzero temperatures (i.e., at cryogenic temperatures)

		Nominal composition, %															
Alloy designation	**UNS No.**	**Si**	**Cu**	**Mn**	**Mg**	**Cr**	**V**	**Ti**	**S_{max}**	**Ni**	**Fe**	**C**	**Mo**	**Al**	**N**	**P_{max}**	**Other**
								Aluminum Alloys									
2014		0.8	4.4	0.8	0.5												
2219			6.3	0.3			0.1	0.06									0.18 Zr
5083				0.7	4.4	0.15											
6061		0.6	0.28		1.0	0.20											
7039		0.1	0.05	0.25	2.8	0.20		0.05			0.2						3.0 Zn
7075			1.6		2.5	0.23											5.6 Zn
								Copper and Copper Alloys									
C 17200 Beryllium copper			98.1														1.9 Be
C 26000 Cartridge brass, 70%			70.0														30 Zn
								High Nickel Alloys									
Hastelloy C	No 5500	0.5	0.1	0.5		15.5				Rem	5.5	0.07	16				1.5Co, 4.0W
Inconel 706	No 9706	0.1		0.10		16		1.7		39–44	Rem	0.04		0.35 max			3.0 (Nb + Ta)
Inconel 718	No 7718					18.6		0.9		Rem	18.5	0.04	3.1.	0.4			5.0 Nb
Inconel X 750				0.7		15.0		2.5		Rem	6.8	0.04		0.8			0.85 Nb
								Austenitic Stainless Steel									
304	S 30400 (AISI 304)	0.03		2.0 max		18–20			1.0	8–12		0.08 max				0.045	
310S	S 31008 (AISI 310)	0.03		2.0 max		24–26			1.5	19–22		0.08 max				0.045	
347	S34700 (AISI 347)	0.03		2.0 max		17–19			1.0	9–13		0.08 max				0.045	(10C)(Nb + Tb)
Pyromet 538				9.5		20			0.15	7.0		0.02			0.2		
Nitromic 70				8.0		17			3.5	8.5		0.07			0.1		
Kromare 5S		0.05		9.3		15.5	0.16		0.05	23		0.03	2.2	0.02	0.17	0.005	0.008Zr, 0.016B
A 286				1.4		15	0.3	2.0	0.4	2.6		0.05	1.25	0.20	2.0		0.005B
								Titanium and Titanium Alloys									
								O_{max}	Sn	H_{max}							
Ti-5Al-3.5Sn								0.20	2.0–3.0	0.02	0.5 max	0.15 max		4.0–6.0	0.07 max		$0.30M_{max}$
Ti-5Al-2.5Sn (EL1)								0.12	2–3	0.018		0.2 max	0.08 max	4.7–5.6	0.05 max		
Ti-6Al-4V (EL1)							3.5–4.5	0.13		0.015 max	0.15 max	0.15 max	0.08 max	5.5–6.5	0.05 max		

TABLE 1-46
Typical tensile properties and fracture toughness of structural alloys at sub-zero temperature (i.e. cryogenic temperature)

Alloy and condition	Temperature °C	Temperature °F	Form	Tensile strength, σ_{st} MPa	Tensile strength, σ_{st} kpsi	Yield strength, σ_{sy} MPa	Yield strength, σ_{sy} kpsi	Elongation, %	Reduction in area, %	Room temperature yield strength, σ_{syr} MPa	Room temperature yield strength, σ_{syr} kpsi	Fracture toughness K_{IC} (J) MPa$\sqrt{m}$	Fracture toughness K_{IC} (J) kpsi$\sqrt{m}$	Specimen design	Orientation	Uses and remarks
Aluminum Alloys																
2014-T651 temper, L.O.	24	75	Plate	310	44.9	290	42.2	16	50	432	62.7	23.2	21.2	Bend	T.L.	Possess high strength at room
	−196	−320		400	58.3	335	48.9	23	48			28.7	26.1			temperature and sub-zero temperature.
	−269	−452		485	70.1	380	55.0	26	42							
2219-T62 temper, L.O.	24	75	Sheet	415	60.2	290	41.9	10		382	55.4			Bend	T.S.	High toughness at room and sub-zero
	−196	−320		460	66.5	345	50.2	11								temperatures, used for liquid oxygen
	−253	−423		545	78.8	370	53.6	14								and liquid hydrogen tanks for space
	−269	−452		650	94.5	390	55.2	23								shuttle.
2219-T87 temper, L.O.	24	75	Plate	465	67.8	380	56.3	11	26	382	55.4	39.9	36.3	Bend, CT	T.S.	Fracture toughness values in
												(28.8)	(26.2)			parentheses refer to specimen design
	−196	−320		585	84.5	460	66.6	13	25			46.5	42.4			C.T.
												(34.5)	(31.4)			
	−253	−423		675	97.6	490	71.0	14	21			52.5	48.0			
												(37.2)	(34.0)			
	−269	−452		675	97.6	510	74.2	15	23							
5083-H113, L.O.	24	75	Plate	335	48.5	235	34.2	15	23	142*	20.6*	27.0*	24.6*	C.T.	T.L.	* Fracture toughness values are for 5083-
	−196	−320		465	67.1	27.5	39.6	31	31			43.4[b]	39.5[b]			O, i.e., K_{IC} (J). 5083-O is not heat
	−253	−423		620	90.0	305	43.9	30	24							treatable and used in annealed (O)
	−269	−452		590	85.8	280	40.5	29	28			48.0*	43.7*			condition. Used to build liquefied
																natural gas (LNG) spherical tanks in
																ships.
6061-T6 temper, L.O.	24	75	Sheet	320	46.3	290	42.2	12								Aluminum alloys 6061 in the T6 temper
	−196	−320		425	61.8	340	49.6	18								have the same strength and ductility at
	−253	−423		495	72.0	365	52.6	26								both room and sub-zero temperatures.
6061, T651 temper, L.O.	24	75	Plate	310	44.9	290	42.2	16	50	289	41.9	29.1	26.5	Bend	T.L.	
	−196	−320		400	58.3	335	48.9	23	48			41.6	37.9			
	−269	−452		485	70.1	380	55.0	26	42							
7039, T6 temper, L.O.	24	75	Sheet	455	66.0	410	59.8	11		381	55.3	32.3	29.4	Bend	T.L.	7039 has good combination of strength
	−196	−320		575	83.2	495	72.0	15				33.5	30.5			and fracture toughness at room and at
	−253	−423		665	96.2	535	77.4	14								−196 °C
7075, T 651 temper, L.O.	24	75	Plate	580	84.2	530	77.1	10	14	536	77.7	22.5	20.5	Bend	T.L.	Used for plate of 7075-T6 for the inner
	−196	−320		705	102	650	94.4	7	10			27.6	25.1			tank skirt between the liquid oxygen
	−269	−452		825	120	770	112	6	9							and liquid hydrogen sections of the
7075, T 7351 temper, L.O.	24	75	Plate	525	76.2	455	66.2	10	22	403	58.5	35.9	32.7			external tank of the space shuttle.
	−196	−320		675	98.2	570	82.5	11	14			32.1	29.2			Improves ductility and notch toughness
	−269	−452		760	110	605	88.1	11	12							of 7075 alloy at cryogenic temperature
																processing it to the T7351 temper.

TABLE 1-46
Typical tensile properties and fracture toughness of structural alloys at sub-zero temperature (i.e. cryogenic temperature) (*Cont.*)

Alloy and condition	Temperature		Form	Tensile strength, σ_{st}		Yield strength, σ_{sy}		Elongation, %	Reduction in area, %	Room temperature yield strength, σ_{syr}		Fracture toughness K_{IC} (J)		Specimen design	Orientation	Uses and remarks
	°C	°F		MPa	kpsi	MPa	kpsi			MPa	kpsi	MPa$\sqrt{m}$	kpsi$\sqrt{m}$			
Copper and Copper Alloys (L.O.)																
C26000 03 temper ($\frac{3}{4}$ hard)	24	75	Bar	655	95.2	420	61.0	14	58							Tensile and fatigue properties of copper
	−196	−320		805	117	475	68.5	28	63							alloys increase as the testing
	−253	−423		910	132	505	73.5	32	58							temperature decreased. Used in
C17200 TD02 temper	24	75	Sheet	620	90	550	80	15								stabilizers, components of the windings
(Solution treated, cold	−196	−320		805	117	690	100	37								in superconducting magnets, solenoids
worked to $\frac{1}{2}$ hard)	−253	−423		945	137	750	109	45								and power cables at super
																temperatures.
High-Nickel Alloys																
Hastelloy C, cold rolled	24	75	Sheet	1140	165	1000	145	13								† Fracture toughness values refer to K_{IC}
20%, L.O.	−196	−320		1520	220	1280	186	32								(J). These high nickel alloys exhibit
	−253	−423		1740	252	1380	200	33								excellent combinations of strength,
Inconel 706 (VIM-VAR)	24	75	Forged	1260	183	1050	152	24	33	1065	154	133†	121†	C.T.	C.R.	toughness, and ductility over the entire
STDA	−196	−320	billets	1570	228	1200	174	29	33							range of subzero temperatures. Used in
	−269	−452		1680	243	1250	181	30	33			157†	143†			energy related equipments such as
																superconducting motors and
																generators.
Inconel 718, L.O.	24	75	Bar	1410	204	1170	170	15	18	1170*	170*	96.4*	87.8*	C.T.		* Refer to STDA alloy.
[Aged $\frac{3}{4}$h at 982°C	−196	−320		1650	239	1340	197	21	20			103	94			The fatigue strengths of high-nickel
(1800°F)]																alloys are higher at cryogenic
	−269	−452		1810	263	1410	204	21	20			112	102			temperature than at room temperature.
GTA weld in Inconel	24	75	Sheet	1290	187	860	125	22	–	825	120			C.T.		$^{\#}$ K_{IJ} (J), fusion zone, gas tungsten arc
X-750 sheet, X-750 filler	−196	−320		1540	224	945	137	50								weld (GTA).
metal, aged 20 h at 700°C	−253	−423		1660	241	1020	148	28					134$^{\#}$	122$^{\#}$		‡ K_{IC} (J), vacuum electron beam weld
	−269	452	Weldment										176‡	160‡		
																(VEB). Used in construction of storage
Ferritic Nickel Steels																tanks for liquefied hydrocarbon gases,
A645 (5Ni Steel), L.O.	24	75	Plate	715	104	530	76.8	32	72							structures and machineries in cold
quenched, tempered,	−162	−260		930	135	570	82.9	2.8	68	535	77.5	196	178			regions.
reversion annealed.	−196	−320		1130	164	765	111	30	62			87.1	79.3			
	−269	−452										58.4	53.2			
Austenitic Stainless Steels																
304 annealed, L.O.	24	75	Sheet	660	95.5	295	42.5	75	–							Austenitic stainless steels are used
	−196	−320		1650	236	425	55.0	42	–							extensively for subzero temperature
	−269	−452		1700	247	570	82.5	30	–							applications to −269°C.
310 S annealed, T.O.	24	75	Forging	330	48	580	84	40	76	260	37.9				T.L.	† Welding process, SMA, Filler, 310S.
	−196	−320		670	97	1070	155	46	67							^{b} In weld fusion zone, as welded.

TABLE 1-46
Typical tensile properties and fracture toughness of structural alloys at sub-zero temperature (i.e. cryogenic temperature) (*Cont.*)

Alloy and condition	Temperature °C	°F	Form	Tensile strength, σ_{st} MPa	kpsi	Yield strength, σ_{sy} MPa	kpsi	Elongation, %	Reduction in area, %	Room temperature yield strength, σ_{syr} MPa	kpsi	Fracture toughness K_{IC} (J) MPa$\sqrt{m}$	kpsi$\sqrt{m}$	Specimen design	Orientation	Uses and remarks
310 S annealed, T.O.	−269	−452	Plate,	825	120	1105	160	26	24	–	–	259	236			Strength of these steels is increased by
	−269	−452	Weldment[†,a]									116[b]	106[b]			rolling or cold drawing at −196°C.
347 annealed, L.O.	24	75	Sheet	650	94	255	57	52								Used in liquid hydrogen and liquid
	−196	−320		1365	198	420	61	47								oxygen tank construction in Atlas and
	−253	−423		1610	234	435	63	35								Centaur rockets. Type 304 stainless
304 hard cold rolled, L.O.	24	75	Sheet	1320	191	1190	173	3								steels used in piping, tubing, and valves.
	−196	−320		1900	276	1430	208	29								Used in transfer of oxygen for storage
	−253	−423		2010	292	1560	226	2								tanks. Cast steels are used for Bubble
310, 75% cold reduced,	24	75	Sheet	1180	171	1100	160	3								Chambers, and for cylindrical magnet
L.O.	−196	−320		1720	249	1540	223	10								tubes for superconducting magnets.
	−253	−423		2000	290	1790	259	10								[‡] Welding process: GTA.
Pyromet 538 annealed	24	75	Plate	415	60	725	105	51	74	340	49	–	–		T.L.	Filler: Pyromet 538.
Pyromet 538 STQ	−196	−320		1005	146	1455	211	48	61			275[a]	250[a]			Fracture toughness values refer to
																Pyromet 538 STQ.
	−269	452	Plate	1240	180	1650	239	31	24			181	165 at −269°C (−452°F)			[a] Shielded metal arc weld.
			Weldment[c]									82[b]	74[b] at −269°C (−452°F)			[b] In weld fusion zone, as welded.
			Weldment[a]									175[b]	159[b] at −269°C (−452°F)			[c] Gas tungsten arc weld.
Nitronic 60, annealed, L.O.	24	75	Bar	750	109	400	58.1	66	79							
	−196	−320		1500	218	695	101	60	66							
	−253	−452		1410	204	860	125	24	27							
Kromarc 58 annealed	24	75	Plate	495	72	915	133	36	61						T.L.	[*] Welding process: GTA.
plate, tested as welded*, L.O.	−196	−320		855	124	1325	192	46	41							Filler: Kromrc 58.
Kromarc 58 STQ	−269	−452	Plate	1060	154	1440	209	33	40	370	53.8	214	195			Kromrc is used for structural
			Weldament[c]									155[b]	141[b]			appliances.
A-286 annealed sheet, welded	24	75	Sheet	600	87	860	125	11								Prototype super-conducting
and age hardened, L.O.	−196	−320		745	108	1145	166	16								generators
A-286 STA	−253	−423		870	126	1280	186	15								
	24	75	Bar							610	88.2	125	114		T.S.	A-286 alloy develops good strength,
	−196	−320										123	112			with good ductility and notch
	−269	−452										118	107			toughness in the cryogenic
	24	75	Plate							820	119	161	146		L.T.	temperature range.
	−269	−452										179	163			
	−269	−452	Weldament[c]									247[b]	225[b]			

TABLE 1-46
Typical tensile properties and fracture toughness of structural alloys at sub-zero temperature (i.e. cryogenic temperature) (*Cont.*)

Alloy and condition	Temperature °C	Temperature °F	Form	Tensile strength, σ_{st} MPa	Tensile strength, σ_{st} kpsi	Yield strength, σ_{sy} MPa	Yield strength, σ_{sy} kpsi	Elongation, %	Reduction in area, %	Room temperature yield strength, σ_{syr} MPa	Room temperature yield strength, σ_{syr} kpsi	Fracture toughness K_{IC} (J) MPa$\sqrt{m}$	Fracture toughness K_{IC} (J) kpsi$\sqrt{m}$	Specimen design	Orientation	Uses and remarks
								Titanium and Titanium Alloys								
Ti-5 Al-2.5 Sn, nominal	24	75	Sheet/	850	123	795	115	16		875	127	71.8	65.4	C.T.	L.T.	Ti-5Al-2.5Sn and Ti-6Al-4V, titanium
interstitial annealed, L.O.	−196	−320	Plate	1370	199	1300	188	14		875	127	53.4	48.6	Bend	L.T.	alloys have high strength to weight
	−253	−423		1700	246	1590	231	7		875	127			Bend	L.T.	ratio at cryogenic temperatures and
Ti-5 Al-2.5 Sn (EL1)	24	75	Sheet/	800	116	740	107	16		705	102			C.T.	L.T.	preferred alloys at temperatures of
annealed, L.O.	−196	−320	Plate	1300	188	1210	175	16		705	102	−111	−101	C.T.	L.T.	alloys at temperatures of −196°C to
	−253	−423		1570	228	1450	210	10				89.6	81.5	Bend	L.T.	−269°C (−320°F to −452°F). Used in
Ti-6 Al-4 V (EL1) as	24	75	Forging	970	141	915	133	14	40	830	120			C.T.	L.T.	spherical pressure vessels in Atlas and
forged	−196	−320		1570	227	1480	214	11	31			610	55.5			Centaur Rockets, the Apollo and
	−253	−423		1650	239	1570	227	11	24							Saturn launch Boosters and Lunar
	−269	−452										54.1	49.2			Modules. Should not be used at cryogenic temperatures for storage or transfer of liquid oxygen, since the condensed oxygen will cause ignition during abrasion.

AAM, air arc melted. C.T., compact toughness. GMA, gas metal arc welding process. GTA, gas tungsten arc weld. L.O., longitudinal orientation. S.T., solution treated. STDA, solution treated and double aged. VAR, vacuum arc remelted. VEB, vacuum electron beam weld. VIM, vacuum induction melted. W, weld.
Source: *Metals Handbook* Desk Edition, ASM International, 1985, Materials Park, OH 44073-0002 (formerly The American Society for Metals, Metals Park, OH 44073, 1985).

TABLE 1-47
Typical properties of wood[a] of clear material of section 50 mm × 50 mm (2 in × 2 in), as per ASTM D143

Kind of wood	Specific gravity G_m ovendry volume	Density[b], D		Shrinkage[c]		Static bending: Modulus of rupture		Static bending: Modulus of elasticity, E		Maximum[d] crushing strength, σ_{scr}		Compression[a] proportionality limit, σ_{scp}		Tensile strength[e,f], σ_{st}		Impact bending in a drop of 222 N (50 lbf) hammer		Shear[d] strength, τ_s		Hardness average of R and T
		kN/m³	lbf/ft³	Rad	Tan	MPa	kpsi	GPa	Mpsi	MPa	kpsi	MPa	kpsi	MPa	kpsi	mm	in	MPa	kpsi	
Softwoods																				
Cedar, western red	0.34	3.62	23	2.4	5.0	51.71	7.5	7.65	1.11	31.44	4.56	3.17	0.46	1.52	0.22	430	17	5.93	0.86	350
Cypress	0.48	5.06	32	3.8	6.2	73.09	10.6	9.93	1.44	43.85	6.36	5.38	0.78	1.86	0.27	864	34	6.89	1.00	510
Douglas fir, coast region	0.51	5.37	34	4.8	7.6	85.50	12.4	13.45	1.95	49.92	7.24	5.52	0.80	2.34	0.34	787	31	8.00	1.16	710
Hemlock, eastern	0.43	4.42	28	3.0	6.8	61.37	8.9	8.28	1.20	37.30	5.41	4.48	0.65	–	–	533	21	7.31	1.06	500
Hemlock, western	0.44	4.6	29	4.3	7.0	77.11	11.3	11.31	1.64	49.02	7.71	3.79	0.55	2.34	0.34	660	26	6.62	1.25	540
Larch, western	0.59	6.00	38	4.5	9.1	90.33	13.10	12.90	1.87	52.68	7.64	6.76	0.98	3.00	0.43	889	35	9.38	1.36	830
Pine, red	0.47	4.90	31	3.8	7.2	75.85	11.00	11.24	1.63	41.85	6.07	4.14	0.60	3.17	0.46	660	26	8.76	1.21	560
Pine, ponderosa	0.42	4.42	28	3.9	6.3	64.81	9.4	8.90	1.29	36.68	5.32	4.00	0.58	2.90	0.42	483	19	7.79	1.13	460
Pine, eastern white	0.37	3.62	24	2.1	6.1	59.30	8.6	8.55	1.24	33.10	4.80	3.03	0.44	2.18	0.31	457	18	6.21	0.90	380
Pine, western white	0.42	4.27	27	2.6	5.3	66.88	9.7	10.10	1.46	34.75	5.04	3.24	0.47	–	–	584	23	7.17	1.04	420
Redwood	0.42	4.42	28	2.6	4.4	69.00	10.0	9.24	1.34	42.40	6.15	4.83	0.70	1.66	0.24	483	19	6.48	0.94	480
Spruce, sitka	0.42	4.42	28	4.3	7.5	70.33	10.2	10.83	1.57	38.68	5.61	4.00	0.58	2.55	0.37	635	25	7.93	1.15	510
Spruce, white	0.45	4.42	28	4.7	8.2	67.57	9.8	9.24	1.34	37.72	5.47	3.17	0.46	2.48	0.36	508	20	7.45	1.08	480
Hardwoods																				
Ash, white	0.64	6.64	42	4.9	7.9	106.18	15.4	12.20	1.77	51.10	7.41	8.00	1.16	6.48	0.94	1092	43	13.45	1.95	1320
Beech	0.67	7.11	45	5.1	11.0	102.74	14.9	11.86	1.72	50.33	7.30	6.96	1.01	7.00	1.01	1041	41	13.86	2.01	1300
Birch, yellow	0.66	6.80	43	7.2	9.2	114.46	16.6	14.55	2.11	56.33	8.17	6.69	0.97	6.34	0.92	1397	55	13.00	1.88	1260
Cherry, black	0.53	5.53	35	3.7	7.1	84.80	12.3	10.27	1.49	48.95	7.11	4.76	0.69	3.86	0.56	737	29	11.72	1.70	950
Cottonwood, eastern	0.43	4.42	28	3.9	9.2	58.60	8.5	9.45	1.37	33.85	4.91	2.55	0.37	4.00	0.58	508	20	6.41	0.93	430
Elm, American	0.55	5.53	35	4.2	9.5	81.36	11.8	9.24	1.34	38.06	5.52	4.76	0.69	4.55	0.66	990	39	10.41	1.51	830
Elm, rock	0.66	7.00	44	4.8	8.1	102.05	14.8	10.62	1.54	48.60	7.05	8.48	1.23	–	–	1422	56	13.24	1.92	1320
Sweetgum	0.55	5.69	36	5.4	10.2	86.19	12.5	11.31	1.64	43.58	6.32	4.28	0.62	5.24	0.76	813	32	11.03	1.6	850
Hickory. shagbark	0.77	7.90	50	7.0	10.5	139.28	20.2	14.89	2.16	63.50	9.21	12.14	1.76	–	–	1702	67	16.75	2.43	–
Mahogany (swietenia spp)	0.51	5.37	34	3.5	4.8	79.02	11.46	10.34	1.50	46.88	6.80	7.58	1.10	5.17	0.75	–	–	8.48	1.23	800
Maple, sugar	0.68	6.95	44	4.9	9.5	108.94	15.80	12.62	1.83	53.98	7.83	10.14	1.47	–	–	483	19	16.06	2.33	1450
Oak, red, northern	0.66	6.95	44	4.0	8.2	98.60	14.30	12.55	1.82	46.61	6.76	7.00	1.01	5.52	0.80	1092	43	12.27	1.78	1290
Oak, white	0.71	7.58	48	5.3	9.0	104.80	15.20	12.27	1.78	51.30	7.44	7.38	1.07	5.52	0.80	940	37	13.80	2.00	1360
Tupelo, black	0.55	5.53	35	4.4	7.7	66.20	9.60	8.27	1.20	38.06	5.52	6.41	0.93	3.44	0.50	559	22	9.24	1.34	810
Yellow poplar	0.45	4.58	29	4.2	7.6	69.64	10.10	10.89	1.58	38.20	5.54	3.45	0.50	3.72	0.54	610	24	8.21	1.19	540
Walnut, black	0.56	6.00	38	5.2	7.1	100.67	14.6	11.58	1.68	52.26	7.58	7.00	1.01	4.76	0.69	864	34	9.45	1.37	1010

[a] Seasoned wood at 12% moisture. [b] Seasoned wood at 12% moisture content. [c] Percent from green to ovendry condition based on dimensions when green. [d] Parallel to grain. [e] Perpendicular to grain. [f] Height of drop of 222 N (50 lbf) hammer for failure, mm (in). Rad, radially. Tan, tangentially. [g] Tensile strength parallel to grain may be taken as equal to modulus of rupture in bending.
Source: Extracted from *Wood Handbook* and the U.S. Forest Products Laboratory.

TABLE 1-48
Mechanical and physical properties of typical dense[a] pure refractories

Material	Density		Modulus of rupture, σ_{sr}				Modulus of elasticity, E		Linear coefficient[b] of expansion, α		Thermal conductivity, K at				Specific heat, c		Fusion point		Thermal stress resistance	Electrical resistivity, Ω cm[c]	
			21°C	70°F	982°C	1800°F	21°C	70°F			100°C	982°C	212°F	1800°F						70°C	1800°F
	g/m^3	lb/in^3	MPa	kpsi	MPa	kpsi	GPa	Mpsi	μm/m°C	μin/in°F	W/(m^2 °C/m)		Btu/(ft^{2}h°F/in)		kJ/kg°C	Btu/lb$_m$ °F	°C	°F		(21°C)	(982°C)
Alumina (Al_2O_3)	3.97	0.143	689	100	414	60	365	53	9.0	5.0	47040	12320	210	55	1.09	0.26	2032	3690	Good	$>10^{14}$	10^7
Beryllium oxide (BeO)	3.03	0.110	138	20	69	10	310	45	8.8	4.9	324800	29120	1450	130	2.09	0.50	2571	4660	Very good	$>10^{14}$	10^8
Magnesium oxide (MgO)	3.58	0.129	97	14	83	12	214	31	13.5	7.5	53760	10528	240	47	1.05	0.25	2799	5070	Poor	$>10^{14}$	10^7
Thoria (ThO_2)	10.00	0.361	83	12	48	7	145	21	9.0	5.0	13888	4480	62	20	0.25	0.06	3049	5520	Fair	$>10^{14}$	10^5
Zirconia (ZrO_2)	5.60	0.202	138	20	103	15	152	22	9.9	5.5	33600	29120	15	15	0.59	0.14	2538	4600	Fair	10^8	500
Uranium oxide (UO_2)	10.96	0.396	83	12			172	25	10.1	5.6	12992	4480	58	20	0.25	0.06	2799	5070	Fair		
Silicon carbide (SiC)	3.22	0.116	166	24	166	24	469	68	4.0	2.2	87360	32480	390	145	0.84	0.20	2760	5000[d]	Excellent	10	
Boron carbide (BC)	2.52	0.097	345	50	276	40	290	42	4.5	2.5	44800	32480	200	145	1.51	0.36	2449	4440	Good	0.5	
Boron nitride (BN)	2.25	0.0813	48	7	7	1	83	12	4.7	2.6	33600	29120	150	130	1.63	0.39	2760	5000	Good	10^{10}	104
Molybdenum silicide ($MoSi_2$)	6.20	0.224	689	100	276	40	345	50	9.2	5.1	49280	22400	220	100	0.46	0.11	2143	3890	Good	10^{-6}	
Carbon (C)	2.22	0.0802	21	3	28	4	14	2	4.0	2.2	194880	64960	870	290	1.42	0.34	3871	7000	Good	10^{-3}	10^{-2}

[a] Porosity: 0 to 5%.
[b] Between 20°C (65°F) and 982°C (1800°F).
[c] Multiply the values by 0.393 in to obtain electrical resistivity in units of Ω-in.
[d] Stabilized.
Courtesy: Extracted from *Mark's Standard Handbook for Mechanical Engineers*, 8th edition, McGraw-Hill Book Company, New York, 1978, and Norton *Refractories*, 3rd edition, Green and Stewart, ASTM Standards on *Refractory Materials Handbook* (Committee, C-8), 1.

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