

Cutting Data for Turning of Steel



Edmund Isakov, Ph.D.

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Introduction

Machining is one of the most important manufacturing processes, which remove unwanted material in the form of chips from a workpiece. Material removal operations are among the most expensive; in the United States alone, more than \$100 billion were spent on machining in 1999. These high costs put tremendous economic pressures on production managers and engineers as they struggle to find ways to increase productivity (Ref 3, p.v).

Machining processes are performed on a wide variety of machine tools. The primary chip formation processes are turning, milling, drilling, shaping, and abrasive machining. The majority of industrial applications of machining are in metals. In spite of their complexity, metal cutting processes are widespread in the industrial world. Metal cutting processes consist of independent or input variables and dependent variables.

Independent (input) variables are:

- Workpiece materials
- Cutting tool materials and geometry
- Cutting parameters

Machine tool operators and manufacturing engineers have direct control over the independent variables and select them when setting up the machining process.

Dependent variables are:

- Cutting forces
- Power consumption
- Surface finish
- Cutting tool conditions

Dependent variables are determined by the machining process based on the prior selection of the independent variables. Therefore, manufacturing personnel do not have direct control over dependent variables.

Workpiece materials (one of the independent variables) have been described by Edmund Isakov in the book published in 2000 (Ref 4). Dependent variables: **Cutting forces** and **Power consumption** were described in the book and software by Edmund Isakov published in 2004 (Ref 5) and in 2005 (Ref 6) respectively.

The purpose of this book is to provide recommendations for selecting **Machining parameters** in relationship with **Cutting tool materials** and **Workpiece materials**.

This book, which complements the author's previous publications, will be useful for setting maximum productivity from machine tools when turning of steels.

Preface

This book provides machining recommendations for turning, which is one of the major metalcutting processes. Rough turning removes more chips and requires more machining power than milling, drilling, and boring. Machining recommendations relate to cutting speeds, feed rates, and depth of cuts. Such recommendations depend on the workpiece materials, their properties, and the type of the cutting tool materials. Workpiece materials described in this book are the most commonly used grades of carbon, alloy, stainless, and tool steels. Cutting tool materials are high-speed steels, cemented carbides, cermets, ceramics, and polycrystalline cubic boron nitride (PCBN).

In 1966, Metcut Research Associates Inc. published its first edition of *Machining Data Handbook*, which became the most important source of machining data for the metalcutting industry. This Handbook had two more editions: the second edition in 1972 and the third edition in 1980. The third edition had several printings; its sixth printing includes Volumes 1 and 2, which were published in 1987 (Ref 1, Ref 2).

For the last two decades, the metalcutting industry has undergone dynamic changes. New cutting tool materials have been developed. In the year 2000, more than 70% of all cemented carbide inserts purchased were coated by chemical vapor deposition (CVD) and physical vapor deposition (PVD). Cermets, ceramics, and polycrystalline cubic boron nitride cutting tools are becoming more popular when machining hardened steels.

Thus, the machining recommendations of the 1980s are considered as starting cutting parameters that require certain adjustments in accordance with today's metalcutting technology. The new book *Cutting Data for Turning of Steel* reflects such adjustments.

In addition to *Machining Data Handbook* (Ref 1, Ref 2) and *Machining, Metals Handbook* (Ref 3), the new book *Cutting Data for Turning of Steel* will be useful to manufacturing engineers and managers, machine shop supervisors, machine tool operators, NC programmers, and cutting tool engineers and designers.

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Chapter 1

Mechanical Properties of Steel

Steels represent the most widely-used category of metallic material, primary because they can be manufactured relatively inexpensively in large quantities to very precise specifications (Ref 7, p.140).

Hardness, tensile strength, and machinability of steels are the major mechanical properties described in this chapter. These properties are taken into consideration when selecting machining parameters.

Classification of steels by commercial name or application is the most common system consisting of the following groups: carbon steels, alloy steels, stainless steels, and tool steels (Ref 8, pp.1, 73, 243, and 431).

1.1. Hardness

Hardness is a measure of the resistance of a material to surface indentation or abrasion. There is no absolute scale for hardness. In order to express hardness quantitatively, each type of test has its own scale that defines hardness. Indentation hardness obtained through static methods is measured by Brinell, Rockwell, Vickers, and Knoop tests. Hardness without indentation is obtained by the dynamic (rebound) method. The typical dynamic method is the Scleroscope hardness test, also known as the Shore method.

Traditionally, selections of machining parameters for steel have been based on Brinell or Rockwell hardness of the work materials, the cutting tool materials (high-speed steels, cemented carbides, cermets ceramics, and cubic boron nitride), and cutting tool geometry (Ref 1 and 8).

1.1.1. Brinell hardness

Hardness of a wide variety of materials is determined by the Brinell test, which consists of applying a constant load, usually between 500 and 3000 kgf, for a specific time (10 to 30 seconds) using a 5- or 10-mm-diameter ball.

Brinell hardness numbers (HB) of carbon and alloy steels in the annealed, normalized, and quenched-and-tempered conditions are determined by forcing a 10-mm-diameter ball made of hardened steel or tungsten carbide into the workpiece under the 3000-kgf load. The most accurate readings are between 81 HB and 444 HB when hardened steel ball indenters are used. Tungsten

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carbide ball indenters are used for hardness numbers between 444 HB and 627 HB (Ref 9, pp.111–113).

The 500-kgf load is used for testing aluminum and copper alloys. However, the same load can be used for testing unhardened steels. Keeping in mind that selection of machining conditions depends on Brinell hardness numbers obtained under the 3000-kgf load, it is necessary to convert Brinell hardness at 500-kgf load into Brinell hardness at 3000-kgf load. Such conversions can be obtained from difficult-to-use, cumbersome tables of the equivalent hardness numbers (Ref 9, pp.109–113). To make hardness conversion friendly, the author used the linear regression method and developed the necessary equations. To obtain high accuracy in conversion, the hardness numbers at 500-kgf load (HB_5) and corresponding hardness numbers at 3000-kgf load (HB_3) were grouped in five tables, each of which contains various numbers of data points.

Statistical treatment of data in each table produced linear regression equations with the correlation coefficients from 0.9962 to 0.9997. These coefficients indicate a strong linear relationship between Brinell hardness at 500-kgf load (HB_5) and Brinell hardness at 3000-kgf load (HB_3).

The following five equations were developed (Appendix 1, Tables 1.1–1.5).

Table 1.1: HB_5 range is 89–99; HB_3 range is 100–112 respectively. The equation for calculating Brinell hardness at 3000-kgf load (HB_C) is

$$HB_C = 1.138 \times HB_5 - 1.052 \quad (1.1)$$

Example of calculation:

$$HB_C = 1.138 \times 89 - 1.052 = 100.230, \text{ rounding off gives: } 100 \text{ (100 } HB_3)$$

$$HB_C = 1.138 \times 99 - 1.052 = 111.610, \text{ rounding off gives: } 112 \text{ (112 } HB_3)$$

Table 1.2: HB_5 range is 101–120; HB_3 range is 114–137 respectively. The equation for calculating Brinell hardness at 3000-kgf load (HB_C) is

$$HB_C = 1.224 \times HB_5 - 9.871 \quad (1.2)$$

Example of calculation:

$$HB_C = 1.224 \times 101 - 9.871 = 113.753, \text{ rounding off gives: } 114 \text{ (114 } HB_3)$$

$$HB_C = 1.224 \times 120 - 9.871 = 137.009, \text{ rounding off gives: } 137 \text{ (137 } HB_3)$$

Table 1.3: HB_5 range is 122–140; HB_3 range is 139–162 respectively. The equation for calculating Brinell hardness at 3000-kgf load (HB_C) is

$$HB_C = 1.311 \times HB_5 - 21.047 \quad (1.3)$$

Example of calculation:

$$HB_C = 1.311 \times 122 - 21.047 = 138.895, \text{ rounding off gives: } 139 \text{ (139 } HB_3)$$

$$HB_C = 1.311 \times 140 - 21.047 = 162.493, \text{ rounding off gives: } 162 \text{ (162 } HB_3)$$

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Table 1.4: HB₅ range is 142–160; HB₃ range is 165–190 respectively. The equation for calculating Brinell hardness at 3000-kgf load (HB_C) is

$$HB_C = 1.369 \times HB_5 - 30.005 \quad (1.4)$$

Example of calculation:

$$HB_C = 1.369 \times 142 - 30.005 = 164.393, \text{ rounding off gives: } 164 \text{ (165 HB}_3\text{)}$$

$$HB_C = 1.369 \times 160 - 30.005 = 189.035, \text{ rounding off gives: } 189 \text{ (190 HB}_3\text{)}$$

Table 1.5: HB₅ range is 163–189; HB₃ range is 195–228 respectively. The equation for calculating Brinell hardness at 3000-kgf load (HB_C) is

$$HB_C = 1.283 \times HB_5 - 14.218 \quad (1.5)$$

Example of calculation:

$$HB_C = 1.283 \times 163 - 14.218 = 194.911, \text{ rounding off gives: } 195 \text{ (195 HB}_3\text{)}$$

$$HB_C = 1.283 \times 189 - 14.218 = 228.269, \text{ rounding off gives: } 228 \text{ (228 HB}_3\text{)}$$

1.1.2. Rockwell hardness

Rockwell hardness testing is applied to most metals and alloys and consists of twenty hardness scales. Rockwell scale B is used to measure hardness (HRB) of steel at the annealed condition. The load is 100 kgf applied to a ¹/₁₆-inch- (1.588 mm-) diameter ball indenter. The accurate readings are between 41 and 100 HRB (Ref 9, pp.111–113). Rockwell scale C is used to measure hardness (HRC) of heat-treated steels harder than 100 HRB. The major load is 150 kgf applied to a 120° spheroconical diamond indenter. The accurate readings are between 20 and 69 HRC (Ref 9, p.77).

Rockwell B hardness numbers and Rockwell C hardness numbers should be converted into the equivalent Brinell hardness numbers measured at 3000-kgf load. The same tables for conversion, mentioned earlier (Ref 9, pp.109–113), can be used. However, linear regression equations developed by the author make such conversions handy and highly accurate. The author applied the same mathematical technique, which was described earlier.

Rockwell B hardness numbers and corresponding Brinell hardness numbers measured at 3000-kgf load were grouped in six tables, each of which contains various numbers of data points.

Statistical treatment of data in each table produced linear regression equations with the correlation coefficients from 0.9971–0.9997. These coefficients indicate a strong linear relationship between Rockwell B hardness numbers and Brinell hardness numbers measured at 3000-kgf load.

The following six equations were developed (Appendix 1, Tables 1.6–1.11).

Table 1.6: HRB range is 62.3–69.8; HB range is 105–121 respectively. The equation for calculating Brinell hardness at 3000-kgf load (HB_C) is

$$HB_C = 2.136 \times HRB - 28.345 \quad (1.6)$$

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Example of calculation:

$$HB_C = 2.136 \times 62.3 - 28.345 = 104.728, \text{ rounding off gives: } 105 \text{ (HB = 105)}$$

$$HB_C = 2.136 \times 69.8 - 28.345 = 120.748, \text{ rounding off gives: } 121 \text{ (HB = 121)}$$

Table 1.7: HRB range is 71.2–79.7; HB range is 124–146 respectively. The equation for calculating Brinell hardness at 3000-kgf load (HB_C) is

$$HB_C = 2.579 \times HRB - 59.950 \quad (1.7)$$

Example of calculation:

$$HB_C = 2.579 \times 71.2 - 59.950 = 123.675, \text{ rounding off gives: } 124 \text{ (HB = 124)}$$

$$HB_C = 2.579 \times 79.7 - 59.950 = 145.596, \text{ rounding off gives: } 146 \text{ (HB = 146)}$$

Table 1.8: HRB range is 80.8–85.0; HB range is 149–163 respectively. The equation for calculating Brinell hardness at 3000-kgf load (HB_C) is

$$HB_C = 3.303 \times HRB - 117.887 \quad (1.8)$$

Example of calculation:

$$HB_C = 3.303 \times 80.8 - 117.887 = 148.995, \text{ rounding off gives: } 149 \text{ (HB = 149)}$$

$$HB_C = 3.303 \times 85.0 - 117.887 = 162.868, \text{ rounding off gives: } 163 \text{ (HB = 163)}$$

Table 1.9: HRB range is 86.0–89.5; HB range is 167–181 respectively. The equation for calculating Brinell hardness at 3000-kgf load (HB_C) is

$$HB_C = 4.031 \times HRB - 180.006 \quad (1.9)$$

Example of calculation:

$$HB_C = 4.031 \times 86.0 - 180.006 = 166.660, \text{ rounding off gives: } 167 \text{ (HB = 167)}$$

$$HB_C = 4.031 \times 89.5 - 180.006 = 180.768, \text{ rounding off gives: } 181 \text{ (HB = 181)}$$

Table 1.10: HRB range is 90.0–95.5; HB range is 183–212 respectively. The equation for calculating Brinell hardness at 3000-kgf load (HB_C) is

$$HB_C = 5.289 \times HRB - 293.668 \quad (1.10)$$

Example of calculation:

$$HB_C = 5.289 \times 90.0 - 293.668 = 182.342, \text{ rounding off gives: } 182 \text{ (HB = 183)}$$

$$HB_C = 5.289 \times 95.5 - 293.668 = 211.432, \text{ rounding off gives: } 211 \text{ (HB = 212)}$$

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Table 1.11: HRB range is 96.4–100.0; HB range is 217–241 respectively. The equation for calculating Brinell hardness at 3000-kgf load (HB_C) is

$$HB_C = 6.736 \times HRB - 432.340 \quad (1.11)$$

Example of calculation:

$$HB_C = 6.736 \times 96.4 - 432.340 = 217.010, \text{ rounding off gives: } 217 \text{ (HB = 217)}$$

$$HB_C = 6.736 \times 100.0 - 432.340 = 241.260, \text{ rounding off gives: } 241 \text{ (HB = 241)}$$

Rockwell C hardness numbers and corresponding Brinell hardness numbers measured at 3000-kgf load were grouped in eight tables, each of which contains various numbers of data points.

Statistical treatment of data in each group produced linear regression equations with the correlation coefficients from 0.9989 to 0.99996. These coefficients indicate a strong linear relationship between Rockwell C hardness numbers and Brinell hardness numbers measured at 3000-kgf load.

The following eight equations were developed (Appendix 1, Tables 1.12–1.19).

Table 1.12: HRC range is 20.5–25.4; HB range is 229–255 respectively. The equation for calculating Brinell hardness at 3000-kgf load (HB_C) is

$$HB_C = 5.284 \times HRC + 120.491 \quad (1.12)$$

Example of calculation:

$$HB_C = 5.284 \times 20.5 + 120.491 = 228.813, \text{ rounding off gives: } 229 \text{ (HB = 229)}$$

$$HB_C = 5.284 \times 25.4 + 120.491 = 254.705, \text{ rounding off gives: } 255 \text{ (HB = 255)}$$

Table 1.13: HRC range is 26.0–29.9; HB range is 258–285 respectively. The equation for calculating Brinell hardness at 3000-kgf load (HB_C) is

$$HB_C = 6.888 \times HRC + 78.838 \quad (1.13)$$

Example of calculation:

$$HB_C = 6.888 \times 26.0 + 78.838 = 257.926, \text{ rounding off gives: } 258 \text{ (HB = 258)}$$

$$HB_C = 6.888 \times 29.9 + 78.838 = 284.789, \text{ rounding off gives: } 285 \text{ (HB = 285)}$$

Table 1.14: HR_C range is 30.0–35.5; HB range is 286–331 respectively. The equation for calculating Brinell hardness at 3000-kgf load (HB_C) is

$$HB_C = 8.195 \times HRC + 39.932 \quad (1.14)$$

Example of calculation:

$$HB_C = 8.195 \times 30.0 + 39.932 = 285.782, \text{ rounding off gives: } 286 \text{ (HB = 286)}$$

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$$HB_C = 8.195 \times 35.5 + 39.932 = 330.854, \text{ rounding off gives: } 331 \text{ (HB = 331)}$$

Table 1.15: HRC range is 36.0–39.8; HB range is 336–369 respectively. The equation for calculating Brinell hardness at 3000-kgf load (HB_C) is

$$HB_C = 8.718 \times HRC + 21.825 \quad (1.15)$$

Example of calculation:

$$HB_C = 8.718 \times 36.0 + 21.825 = 335.673, \text{ rounding off gives: } 336 \text{ (HB = 336)}$$

$$HB_C = 8.718 \times 39.8 + 21.825 = 368.801, \text{ rounding off gives: } 369 \text{ (HB = 369)}$$

Table 1.16: HRC range is 40.0–45.7; HB range is 371–429 respectively. The equation for calculating Brinell hardness at 3000-kgf load (HB_C) is

$$HB_C = 10.057 \times HRC - 31.761 \quad (1.16)$$

Example of calculation:

$$HB_C = 10.057 \times 40.0 - 31.761 = 370.519, \text{ rounding off gives: } 371 \text{ (HB = 371)}$$

$$HB_C = 10.057 \times 45.7 - 31.761 = 427.844, \text{ rounding off gives: } 428 \text{ (HB = 429)}$$

Table 1.17: HRC range is 46.1–49.8; HB range is 433–479 respectively. The equation for calculating Brinell hardness at 3000-kgf load (HB_C) is

$$HB_C = 12.642 \times HRC - 150.881 \quad (1.17)$$

Example of calculation:

$$HB_C = 12.642 \times 46.1 - 150.881 = 431.915, \text{ rounding off gives: } 432 \text{ (HB = 433)}$$

$$HB_C = 12.642 \times 49.8 - 150.881 = 478.691, \text{ rounding off gives: } 479 \text{ (HB = 479)}$$

Table 1.18: HRC range is 50.0–55.2; HB range is 481–564 respectively. The equation for calculating Brinell hardness at 3000-kgf load (HB_C) is

$$HB_C = 15.979 \times HRC - 318.988 \quad (1.18)$$

Example of calculation:

$$HB_C = 15.979 \times 50.0 - 318.988 = 479.962, \text{ rounding off gives: } 480 \text{ (HB = 481)}$$

$$HB_C = 15.979 \times 55.2 - 318.988 = 563.053, \text{ rounding off gives: } 563 \text{ (HB = 564)}$$

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Table 1.19: HRC range is 56.0–58.7; HB range is 578–627 respectively. The equation for calculating Brinell hardness at 3000-kgf load (HB_C) is

$$HB_C = 18.694 \times HRC - 469.983 \quad (1.19)$$

Example of calculation:

$$HB_C = 18.694 \times 56.0 - 469.983 = 576.881, \text{ rounding off gives: } 577 \text{ (HB} = 578\text{)}$$

$$HB_C = 18.694 \times 58.7 - 469.983 = 627.355, \text{ rounding off gives: } 627 \text{ (HB} = 627\text{)}$$

These nineteen highly-accurate linear regression equations should be used to convert Brinell hardness numbers measured at 500-kgf load (five equations), Rockwell B-scale hardness numbers (six equations), and Rockwell C-scale hardness numbers (eight equations) into Brinell hardness numbers at 3000-kgf load.

The other mechanical properties (tensile strength–hardness relationship and machinability ratings) are described for each of the following steel categories: carbon steels, alloy steels, stainless steels, and tool steels.

Concluding Remarks on Hardness

1. Brinell hardness test performed at 3000-kgf load is the most commonly-used test to define the hardness characteristic of a steel.

2. If the hardness numbers of a workpiece are available only in Brinell at 500-kgf load or in Rockwell B-scale, or in Rockwell C-scale, those hardness numbers must be converted into the equivalent Brinell hardness numbers at 3000-kgf load.

3. The author developed nineteen linear regression equations to perform such conversions. There are five equations to convert Brinell hardness numbers measured at 500-kgf load (HB_5) providing 99.1–100% accuracy; six equations to convert Rockwell hardness numbers measured on the B-scale (HRB) providing 99.5–100% accuracy; and eight equations to convert Rockwell hardness numbers measured on the C-scale (HRC) providing 99.7–100% accuracy. These nineteen equations are summarized in Table 1.1.

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Table 1.1. Conversion into Brinell hardness numbers measured at 3000-kgf load – HB_C

Range of Hardness Numbers	Equation to Convert into HB _C	Correlation Coefficient
(89–100) HB ₅	$HB_C = 1.138 \times HB_5 - 1.052$	0.9962
(101–120) HB ₅	$HB_C = 1.224 \times HB_5 - 9.871$	0.9978
(121–140) HB ₅	$HB_C = 1.311 \times HB_5 - 21.047$	0.9988
(141–160) HB ₅	$HB_C = 1.369 \times HB_5 - 30.005$	0.9967
(161–189) HB ₅	$HB_C = 1.283 \times HB_5 - 14.218$	0.9997
(60.0–69.9) HRB	$HB_C = 2.136 \times HRB - 28.345$	0.9990
(70.0–79.9) HRB	$HB_C = 2.579 \times HRB - 59.950$	0.9991
(80.0–85.9) HRB	$HB_C = 3.303 \times HRB - 117.887$	0.9997
(86.0–89.9) HRB	$HB_C = 4.031 \times HRB - 180.006$	0.9971
(90.0–95.9) HRB	$HB_C = 5.289 \times HRB - 293.668$	0.9986
(96.0–100.0) HRB	$HB_C = 6.736 \times HRB - 432.340$	0.9996
(20.0–25.9) HRC	$HB_C = 5.284 \times HRC + 120.491$	0.9997
(26.0–29.9) HRC	$HB_C = 6.888 \times HRC + 78.838$	0.9999
(30.0–35.9) HRC	$HB_C = 8.195 \times HRC + 39.932$	0.99996
(36.0–39.9) HRC	$HB_C = 8.718 \times HRC + 21.825$	0.9997
(40.0–45.9) HRC	$HB_C = 10.057 \times HRC - 31.761$	0.9994
(46.0–49.9) HRC	$HB_C = 12.642 \times HRC - 150.881$	0.9989
(50.0–55.9) HRC	$HB_C = 15.979 \times HRC - 318.988$	0.9998
(56.0–58.9) HRC	$HB_C = 18.694 \times HRC - 469.983$	0.9993

As can be seen from the table, the correlation coefficients range from 0.9962 to 0.99996, indicating high accuracy in converting HB₅, HRB, and HRC hardness numbers into HB_C hardness numbers.

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1.2. Carbon Steels

Carbon steels are by far the most frequently used steel. In 1988 the United States produced 99.9 million tons of steel, including 86.8 million tons, or 86.9% of carbon steel (Ref 7, p.147). The feasibility of using carbon steels depends on whether or not their properties (tensile, yield, and fatigue strengths; impact resistance, need for heat treating, etc.) are suitable for the parts to be used. If the required characteristics can be obtained with carbon steel, most users select this less costly steel.

The American Iron and Steel Institute (AISI) defines carbon steel as follows: “*Steel is considered to be carbon steel when no minimum content is specified or required for chromium, cobalt, molybdenum, nickel, niobium, titanium, tungsten, vanadium or zirconium, or any other element to be added to obtain a desired alloying effect; when the specified minimum for copper does not exceed 0.40 percent; or when the maximum content specified for any of the following elements does not exceed the percentages noted: manganese 1.65, silicon 0.60, copper 0.60*” (Ref 7, p.147).

Sometimes the term *plain carbon steel* is used instead of carbon steel. It is acceptable, but no longer considered best practice. Some of the cutting tool companies — such as KOMET of America (Ref 10), Sandvik Coromant (Ref 11), and WALTER Waukesha (Ref 12) — define carbon steel as *unalloyed steel*; Greenleaf Corporation defines carbon steel as *non-alloy steel* (Ref 13, pp. ATI 04–08). Such definitions are wrong because steel without alloying elements is nothing else but *iron*.

Carbon steels are designated by an identical AISI or SAE (Society of Automotive Engineers) four-digit number. The last two digits indicate the approximate middle of the carbon range expressed in hundredth of one percent. For example, AISI 1020 grade has a carbon content of 0.18–0.23%. The first two digits of the number are also significant. The number **10** indicates non-resulfurized grades with manganese content from 0.25 to 1.00%. These grades include low-carbon, medium-carbon, and high-carbon steels. The number **11** denotes free-machining resulfurized grades. The number **12** indicates free-machining resulfurized and rephosphorized grades. The number **15** indicates nonresulfurized grades with manganese content from 0.75 to 1.65%.

Carbon steels are also designated by UNS (Unified Numbering System). A UNS number is assigned to each chemical composition of a metallic alloy. The UNS designation consists of a letter followed by a five-digit number. Letters **G** or **H** are assigned to carbon steels. An **H** indicates carbon steel produced to prescribed hardenability limits. The initial four digits are the same as the four-digit number assigned by AISI or SAE and the last digit is **0** for the majority of grades. If the last digit is “4”, then the steel contains 0.15 to 0.35% lead. For example, AISI 12L14 is the same as UNS G12144, AISI 1038 is UNS G10380, and AISI 1038H is UNS H10380.

Some AISI–SAE grades are also designated by letters **B** and **L**, placed between the second and third digits, and by the letter **H** after the four digits. Letters **B** and **L** denote grades containing boron and lead respectively. An **H** indicates steel produced to prescribed hardenability limits, for example AISI 1038H, AISI 1045H, and AISI 15B48H.

Carbon steels are divided into six categories: (1) low-carbon steels, medium-carbon steels, and high-carbon steels; (2) free-machining resulfurized steels, free-machining resulfurized and rephosphorized steels; and (3) nonresulfurized high-manganese steels containing more than 1.00% manganese.

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1.2.1. Low-carbon steels

Low-carbon steels (AISI 1005 to AISI 1026) are produced to a range of 0.06–0.28% carbon (C) and to a range of 0.25–1.00% manganese (Mn). Low-carbon steels are limited to 0.040% phosphorus and 0.050% sulfur. Currently, there are sixteen standard grades of low-carbon steels.

The author studied the relationship between the tensile strength (σ) and Brinell hardness (HB) of those grades for which a sufficient number of data points were available. The author applied linear regression analysis and statistical treatment of data. As a result of this study, engineering formulas were developed to calculate tensile strength versus Brinell hardness for the following grades: AISI 1015, 1018, 1020, 1021, and 1025. Applications and mechanical properties of these grades are described below.

AISI 1015 steel is produced to a range of 0.13–0.18% C and 0.30–0.60% Mn. It can be surface hardened by carburizing or cyaniding. This steel is widely used for low-strength applications because of good formability and fair response to moderate machining. The average machinability rating of this steel is 60% at Brinell hardness range of (101–126) HB (Ref 8, p.12).

Notice: Average machinability ratings of carbon steels are expressed in percent and based on AISI 1212 free-machining steel as 100% average machinability.

Heat treatment of 1015 steel provides the following hardness:

- 111 HB when annealed
- 116–126 HB when normalized; hardness increases if the diameter of the workpiece decreases
- 121–217 HB when carburized, quenched in water, and tempered; hardness increases if the diameter of the work-piece decreases.

Surface hardness of the round workpiece after quenching in water depends on its diameter. Hardness decreases if the diameter of the workpiece increases (Ref 8, p. 12):

0.5 in.	36.5 HRC or 340 HB — converted by equation (1.15)
1.0 in.	99.0 HRB or 235 HB — converted by equation (1.11)
2.0 in.	98.0 HRB or 228 HB — converted by equation (1.11)
4.0 in	97.0 HRB or 221 HB — converted by equation (1.11)

Brinell hardness (HB) – tensile strength (σ) relationships for AISI 1015 steel are expressed by the following formulas (Appendix 2, Tables 2.1A and 2.1B):

$$\sigma = 468 \times \text{HB} + 4120 \quad (2.1)$$

$$\sigma = 499 \times \text{HB} \quad (2.2)$$

Linear regression formula (2.1) provides 96.7–99.9% accuracy in calculating tensile strength. This is a formula of a straight line: 468 is the slope, 4120 is the intercept. The correlation coefficient is 0.9967 (Appendix 2, Table 2.1A), indicating a strong linear relationship between tensile

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strength and Brinell hardness.

Statistical formula (2.2) provides 96.5–99.4% accuracy in calculating tensile strength. The number 499 is the arithmetic average obtained by dividing the cumulative tensile strength data by the cumulative Brinell hardness data (Appendix 2, Table 2.1B). The use of the formulas is limited to Brinell hardness range of 100–220 HB.

AISI 1018 steel is produced to a range of 0.15–0.18% C and 0.60–0.90% Mn. The average machinability rating is 70–65% at Brinell hardness range of (101–197) HB.

Heat treatment of 1018 steel provides the following hardness (Ref 8, p.13):

- 101–131 HB when cold drawn at high temperature
- 143 HB when hot rolled, quenched, and tempered
- 111–143 HB when cold drawn
- 163 HB when cold drawn, quenched, and tempered
- 197 HB when carburized, water quenched, and tempered.

The following formulas were developed to calculate tensile strength of 1018 steel depending on its Brinell hardness (Appendix 2, Tables 2.2A and 2.2B):

$$\sigma = 493 \times \text{HB} + 398 \quad (2.3)$$

$$\sigma = 496 \times \text{HB} \quad (2.4)$$

Linear regression formula (2.3) provides 97.3–100% accuracy in calculating tensile strength. The values and definitions of 493 and 398 are similar to those described earlier. The correlation coefficient is 0.9941 (Appendix 2, Table 2.2A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (2.4) provides 97.3–100% accuracy in calculating tensile strength. The value 496 (Appendix 2, Table 2.2B) is similar to that described earlier. The use of formulas (2.3) and (2.4) is limited to Brinell hardness range of 100–165 HB.

AISI 1020 steel is produced to a range of 0.18–0.23% C and 0.30–0.60% Mn. This grade is used for shafts that are not highly stressed, for lightly-stressed gears with hardwearing surfaces and case-hardened pins and chains. The average machinability rating of this steel is 65% at Brinell hardness range of (111–163) HB (Ref 8, pp.16, 17).

Heat treatment of 1020 steel provides the following hardness:

- 111 HB when annealed
- 121–131 HB when normalized; hardness increases if the diameter of the workpiece decreases
- 143–255 HB when carburized, quenched in water, and tempered; hardness increases if the diameter of the workpiece decreases.

Surface hardness of a round workpiece after quenching in water depends on its size. An increase in diameter causes decrease in hardness:

$$0.5 \text{ in. } 40.5 \text{ HRC or } 376 \text{ HB} \text{ — converted by equation (1.14)}$$

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1.0 in. 29.5 HRC or 282 HB — converted by equation (1.11)

2.0 in. 95.0 HRB or 209 HB — converted by equation (1.10)

4.0 in. 94.0 HRB or 203 HB — converted by equation (1.10)

The following formulas were developed to calculate tensile strength of 1020 steel depending on its Brinell hardness (Appendix 2, Tables 2.3A and 2.3B):

$$\sigma = 502 \times \text{HB} - 662 \quad (2.5)$$

$$\sigma = 497 \times \text{HB} \quad (2.6)$$

Linear regression formula (2.5) provides 96.2–99.9% accuracy in calculating tensile strength. The values and definitions of 502 and 662 are similar to those described earlier. The correlation coefficient is 0.9977 (Appendix 2, Table 2.3A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (2.6) provides 96.4–99.8% accuracy in calculating tensile strength. The value 497 (Appendix 2, Table 2.3B) is similar to that described earlier. The use of the formulas is limited to Brinell hardness range of 110–255 HB.

AISI 1021 and 1022 steels are produced to the same amount of carbon ranging from 0.18 to 0.23%. AISI 1021 grade contains 0.60–0.90% Mn, and AISI 1022 grade contains 0.70–1.00% Mn. These grades are used for low-strength fasteners, die pins, motor spindles, and recessed-head screws. The average machinability rating of these steels is 70% at Brinell hardness range of (116–149) HB (Ref 8, p.18).

Heat treatment of these steels provides the following hardness

- 137 HB when annealed
- 131–143 HB when normalized; hardness increases if the diameter of the workpiece decreases
- 149–262 HB when carburized, quenched in water, and tempered; hardness increases if the diameter of the work piece decreases.

Surface hardness numbers of a round workpiece after quenching in water are as follows. An increase in diameter causes decrease in hardness:

0.5 in. 45.0 HRC or 421 HB — converted by equation (1.16)

1.0 in. 41.0 HRC or 381 HB — converted by equation (1.16)

2.0 in. 38.0 HRC or 353 HB — converted by equation (1.15)

4.0 in. 34.0 HRC or 319 HB — converted by equation (1.14)

The following formulas were developed to calculate tensile strength of 1021 and 1022 steels depending on their Brinell hardness (Appendix 2, Tables 2.4A and 2.4B):

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$$\sigma = 521 \times \text{HB} - 2962 \quad (2.7)$$

$$\sigma = 502 \times \text{HB} \quad (2.8)$$

Linear regression formula (2.7) provides 96.9–100% accuracy in calculating tensile strength. The correlation coefficient is 0.9971 (Appendix 2, Table 2.4A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (2.8) provides 97.4–100% accuracy in calculating tensile strength (Appendix 2, Table 2.4B). The use of these formulas is limited to Brinell hardness range of 120–265 HB.

AISI 1025 grade is produced to a range of 0.22–0.28% C and 0.30–0.60% Mn. The applications of this grade are similar to those described for AISI 1020 steel. The average machinability rating is 65% at Brinell hardness range of (101–143) HB (Ref 8, p. 21).

Heat treatment of 1025 steel provides the following hardness:

- 101–131 HB when cold drawn at high temperature
- 116 HB when hot rolled
- 111–143 HB when cold drawn.

The following formulas were developed to calculate tensile strength of 1025 steel depending on Brinell hardness (Appendix 2, Tables 2.5A and 2.5B):

$$\sigma = 485 \times \text{HB} + 1462 \quad (2.9)$$

$$\sigma = 497 \times \text{HB} \quad (2.10)$$

Linear regression formula (2.9) provides 97.8–100% accuracy in calculating tensile strength. The correlation coefficient is 0.9942 (Appendix 2, Table 2.5A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (2.10) provides 97.8–99.8% accuracy in calculating tensile strength (Appendix 2, Table 2.5B). The use of these formulas is limited to Brinell hardness range of 100–145 HB.

Low-carbon steels containing less than 0.15% C (AISI 1005 to AISI 1016) are more difficult to machine than any other grade of carbon steels because they are ductile, gummy, and adhere to the cutting tools. The chip resists separation from the parent material, becomes too long and unmanageable, and tends to develop a built-up edge on a cutting tool. Low-carbon steels in the range of 0.15–0.30% carbon are usually machined satisfactorily in the annealed or normalized conditions.

As a positive feature, low-carbon steels are relatively inexpensive and widely used if the strength of the parts is not an issue.

1.2.2. Medium-carbon steels

Medium-carbon steels (AISI 1029 to AISI 1053) are produced to a range of 0.30–0.55% car-

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bon and to a range of 0.30–1.00% manganese. Medium-carbon steels are limited to 0.040% phosphorus and 0.050% sulfur. Currently, there are sixteen standard grades of medium-carbon steel.

The author studied the relationship between the tensile strength (σ) and Brinell hardness (HB) of those grades for which sufficient number of data points were available. The same treatments of data as for low-carbon steels were applied. As a result of this study, engineering formulas were developed to calculate tensile strength versus Brinell hardness for the following grades: AISI 1030, 1035, 1040, 1045, and 1050.

AISI 1030 grade is produced to a range of 0.28–0.34% C and 0.60–0.90% Mn. This grade is used in manufacturing levers, studs, bolts, nuts, and similar parts. The average machinability rating is 70% at Brinell hardness range of (126–179) HB (Ref 8, pp.22, 23).

Heat treatment of 1030 steel provides the following hardness:

- 126 HB when annealed
- 137–156 HB when normalized; hardness increases if the diameter of the workpiece decreases
- 149–187 HB when quenched in water and tempered; hardness increases if the diameter of the workpiece and tempering temperature decrease.

Surface hardness numbers of a round workpiece after quenching in water are as follows. An increase in diameter causes a decrease in hardness:

0.5 in. 50.0 HRC or 480 HB — converted by equation (1.18)

1.0 in. 46.0 HRC or 431 HB — converted by equation (1.17)

2.0 in. 30.0 HRB or 286 HB — converted by equation (1.14)

4.0 in. 97.0 HRB or 221 HB — converted by equation (1.11)

The following formulas were developed to calculate tensile strength of 1030 steel depending on Brinell hardness (Appendix 2, Tables 2.6A and 2.6B):

$$\sigma = 471 \times \text{HB} + 4376 \quad (2.11)$$

$$\sigma = 498 \times \text{HB} \quad (2.12)$$

Linear regression formula (2.11) provides 98.1–99.8% accuracy in calculating tensile strength. The correlation coefficient is 0.9908 (Appendix 2, Table 2.6A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (2.12) provides 97.6–99.8% accuracy in calculating tensile strength (Appendix 2, Table 2.6B). The use of these formulas is limited to Brinell hardness range of 125–190 HB.

AISI 1035 grade is produced to a range of 0.32–0.38% C and 0.60–0.90% Mn. Applications of this steel are similar to those described for AISI 1030 steel. The average machinability rating is 65% at Brinell hardness range of (131–207) HB (Ref 8, p. 23).

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Heat treatment of 1035 steel provides the following hardness:

- 131–163 HB when cold drawn at high temperature;
- 149–179 HB when cold drawn at low temperature
- 207 HB when quenched in water and tempered.

The following formulas were developed to calculate tensile strength of 1035 steel depending on Brinell hardness (Appendix 2, Tables 2.7A and 2.7B):

$$\sigma = 502 \times \text{HB} - 634 \quad (2.13)$$

$$\sigma = 498 \times \text{HB} \quad (2.14)$$

Linear regression formula (2.13) provides 98.4–99.8% accuracy in calculating tensile strength. The correlation coefficient is 0.9977 (Appendix 2, Table 2.7A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (2.14) provides 98.3–99.9% accuracy in calculating tensile strength (Appendix 2, Table 2.7B). The use of these formulas is limited to Brinell hardness range of 130–210 HB.

AISI 1040 grade is produced to a range of 0.37–0.44% C and 0.60–0.90% Mn. Applications of this steel include bolts for machines, plows, and carriages; cylinder head studs, U-bolts, concrete reinforcing rods, and springs. The average machinability rating is 60% at Brinell hardness range of (149–201) HB (Ref 8, p.27).

Heat treatment of 1040 steel provides the following hardness (Ref 8, p.28):

- 149 HB when annealed
- 167–183 HB when normalized; hardness increases if the diameter of the workpiece decreases
- 156–217 HB when quenched in oil and tempered; hardness increases if the diameter of the workpiece and tempering temperature decrease
- 170–223 HB when quenched in water and tempered; hardness increases if the diameter of the workpiece and tempering temperature decrease.

Surface hardness of a round workpiece depends on its diameter and the heat treatment. After quenching in oil, the hardness numbers are as follows:

- 0.5 in. 28.0 HRC or 272 HB — converted by equation (1.13)
- 1.0 in. 23.0 HRC or 242 HB — converted by equation (1.12)
- 2.0 in. 93.0 HRB or 198 HB — converted by equation (1.10)
- 4.0 in. 91.0 HRB or 188 HB — converted by equation (1.10)

After quenching in water, the hardness numbers are as follows:

- 0.5 in. 54.0 HRC or 544 HB — converted by equation (1.18)

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1.0 in. 50.0 HRC or 480 HB — converted by equation (1.18)

2.0 in. 50.0 HRC or 480 HB — converted by equation (1.18)

4.0 in. 98.0 HRB or 228 HB — converted by equation (1.11)

The following formulas were developed to calculate tensile strength of 1040 steel depending on Brinell hardness (Appendix 2, Tables 2.8A and 2.8B):

$$\sigma = 455 \times \text{HB} + 6954 \quad (2.15)$$

$$\sigma = 493 \times \text{HB} \quad (2.16)$$

Linear regression formula (2.15) provides 97.2–99.9% accuracy in calculating tensile strength. The correlation coefficient is 0.9936 (Appendix 2, Table 2.8A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (2.16) provides 97.4–99.9% accuracy in calculating tensile strength (Appx. 2, Table 2.8B). The use of the formulas is limited to Brinell hardness range of 140–225 HB.

AISI 1045 grade is produced to a range of 0.43–0.50% C and 0.60–0.90% Mn. This steel is used for gears, shafts, axles, studs, and other machine parts. The average machinability rating is 65–55% at Brinell hardness range of (163–212) HB (Ref 8, p.31). Heat treatment of 1045 steel provides the following hardness:

- 163 HB when hot rolled
- 163–187 HB when cold drawn at high temperature
- 170–197 HB when cold drawn at low temperature.

The following formulas were developed to calculate tensile strength of 1045 steel depending on Brinell hardness (Appendix 2, Tables 2.9A and 2.9B):

$$\sigma = 567 \times \text{HB} - 11278 \quad (2.17)$$

$$\sigma = 503 \times \text{HB} \quad (2.18)$$

Linear regression formula (2.17) provides 98.6–99.9% accuracy in calculating tensile strength. The correlation coefficient is 0.9952 (Appendix 2, Table 2.9A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (2.18) provides 97.6–100% accuracy in calculating tensile strength (Appx. 2, Table 2.9B). The use of the formulas is limited to Brinell hardness range of 160–200 HB.

AISI 1050 grade is produced to a range of 0.48–0.55% C and 0.60–0.90% Mn. Applications include piston rods and springs (coil and disc types). The average machinability rating of this steel is 55–45% at Brinell hardness range of (163–229) HB (Ref. 8, p.32).

Mechanical Properties of Steel

Heat treatment of 1050 steel provides the following hardness (Ref 8, p.33):

- 187 HB when annealed
- 201–223 HB when normalized; hardness increases if the diameter of the workpiece decreases
- 197–262 HB when quenched in oil and tempered; hardness increases if the diameter of the workpiece and tempering temperature decrease
- 217–269 HB when quenched in water and tempered; hardness increases if the diameter of the workpiece and tempering temperature decrease.

Surface hardness of a round workpiece depends on its diameter and the heat treatment. After quenching in oil, the hardness numbers are as follows:

- 0.5 in. 57.0 HRC or 596 HB — converted by equation (1.19)
- 1.0 in. 33.0 HRC or 310 HB — converted by equation (1.14)
- 2.0 in. 27.0 HRC or 265 HB — converted by equation (1.13)
- 4.0 in. 98.0 HRB or 228 HB — converted by equation (1.11)

After quenching in water, the hardness numbers are as follows:

- 0.5 in. 64.0 HRC or 722 HB — is beyond the accurate reading (Ref 9, p.110)
- 1.0 in. 60.0 HRC or 653 HB — is beyond the accurate reading (Ref 9, p.111)
- 2.0 in. 50.0 HRC or 480 HB — converted by equation (1.18)
- 4.0 in. 33.0 HRC or 310 HB — converted by equation (1.14)

The following formulas were developed to calculate tensile strength of 1050 steel depending on Brinell hardness (Appendix 2, Tables 2.10A and 2.10B):

$$\sigma = 501 \times \text{HB} - 568 \quad (2.19)$$

$$\sigma = 498 \times \text{HB} \quad (2.20)$$

Linear regression formula (2.19) provides 98.0–100% accuracy in calculating tensile strength. The correlation coefficient is 0.9969 (Appendix 2, Table 2.10A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical form. (2.20) provides 98.0–100% accuracy in calculating tensile strength (Appx. 2, Table 2.10B). The use of the formulas is limited to Brinell hardness range of 160–270 HB.

1.2.3. High-carbon steels

High-carbon steels (AISI 1055 to AISI 1095) are produced to a range of 0.60–1.00% carbon

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and to a range of 0.30–0.90% manganese. High-carbon steels are limited to 0.040% phosphorus and 0.050% sulfur. Currently, there are fourteen standard grades of high-carbon steels.

The author studied the relationship between the tensile strength (σ) and Brinell hardness (HB) of those grades for which sufficient number of data points were available. The same treatments of data as for low-carbon and medium-carbon steels were applied. As a result of this study, engineering formulas were developed to calculate tensile strength versus Brinell hardness for the following grades: AISI 1060, 1080, and 1095.

AISI 1060 grade is produced to a range of 0.55–0.65% C and 0.60–0.90% Mn. Typical applications for this steel include dies, hand tools, battering tools, ring-rolling tools, and wear-resistant parts, which require high strength at low cost. The average machinability rating of this steel after cold drawn processing and annealing is 60% at 183 HB (Ref 8, p.5).

Heat treatment of AISI 1060 grade provides the following hardness (Ref 8, p.36):

- 179 HB when annealed
- 223–229 HB when normalized; hardness slightly increases if the diameter of the workpiece decreases
- 241–302 HB when quenched in oil and tempered; hardness increases if the diameter of the workpiece and tempering temperature decrease.

Surface hardness of a round workpiece after quenching in oil decreases when its diameter increases:

0.5 in. 59.0 HRC or 634 HB — is beyond the accurate reading (Ref 9, p.110)

1.0 in. 34.0 HRC or 319 HB — converted by equation (1.14)

2.0 in. 30.5 HRC or 290 HB — converted by equation (1.14)

4.0 in. 29.0 HRC or 279 HB — converted by equation (1.13)

The following formulas were developed to calculate tensile strength of 1060 steel depending on Brinell hardness (Appendix 2, Tables 2.11A and 2.11B):

$$\sigma = 513 \times \text{HB} - 3597 \quad (2.21)$$

$$\sigma = 499 \times \text{HB} \quad (2.22)$$

Linear regression formula (2.21) provides 97.0–99.7% accuracy in calculating tensile strength. The correlation coefficient is 0.9956 (Appendix 2, Table 2.11A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (2.22) provides 97.1–99.9% accuracy in calculating tensile strength (Appx. 2, Table 2.11B). The use of the formulas is limited to Brinell hardness range of 175–305 HB.

AISI 1080 grade is produced to a range of 0.75–0.88% C and 0.60–0.90% Mn. This steel is used to manufacture coil springs and disc springs for various mechanisms and engineering devices.

Mechanical Properties of Steel

The average machinability rating is 45% at Brinell hardness range of (174–293) HB (Ref. 8, p.43). Heat treatment of 1080 steel provides the following hardness (Ref 8, p.42):

- 174 HB when annealed
- 269–293 HB when normalized; hardness increases if the diameter of the workpiece decreases
- 269–363 HB when quenched in oil and tempered; hardness increases if the diameter of the workpiece and tempering temperature decrease.

Surface hardness of a round workpiece after quenching in oil decreases when its diameter increases:

0.5 in. 60.0 HRC or 653 HB — is beyond the accurate reading (Ref 9, p.111)

1.0 in. 45.0 HRC or 421 HB — converted by equation (1.16)

2.0 in. 43.0 HRC or 401 HB — converted by equation (1.16)

4.0 in. 39.0 HRC or 362 HB — converted by equation (1.15)

The following formulas were developed to calculate tensile strength of 1080 steel depending on Brinell hardness (Appendix 2, Tables 2.12A and 2.12B):

$$\sigma = 511 \times \text{HB} - 2109 \quad (2.23)$$

$$\sigma = 504 \times \text{HB} \quad (2.24)$$

Linear regression formula (2.23) provides 97.5–99.9% accuracy in calculating tensile strength. The correlation coefficient is 0.9969 (Appendix 2, Table 2.12A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (2.24) provides 97.0–99.9% accuracy in calculating tensile strength (Appendix 2, Table 2.12B). The use of the formulas is limited to Brinell hardness range of 170–365 HB.

AISI 1095 grade is produced to a range of 0.90–1.03% C and 0.30–0.50% Mn. This steel is used for wear-resistant parts, high-stress cone disc springs, hot coiled springs, edge tools, plow beams, plowshares, scraper blades, mower knives, and harrow teeth (Ref 8, p.43). The average machinability rating of AISI 1095 steel is 45% at Brinell hardness range of (192–293) HB (Ref 8, p.45).

Heat treatment of 1095 steel provides the following hardness (Ref. 8, p.44):

- 192 HB when annealed
- 255–302 HB when normalized; hardness increases if the diameter of the workpiece decreases
- 262–363 HB when quenched in oil and tempered; hardness increases if the diameter of the workpiece and tempering temperature decrease.

Surface hardness of a round workpiece after quenching in oil decreases when its diameter

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increases:

0.5 in. 60.0 HRC or 653 HB — is beyond the accurate reading (Ref 9, p.111)

1.0 in. 46.0 HRC or 431 HB — converted by equation (1.17)

2.0 in. 43.0 HRC or 401 HB — converted by equation (1.16)

4.0 in. 40.0 HRC or 371 HB — converted by equation (1.16)

The following formulas were developed to calculate tensile strength of 1095 steel depending on Brinell hardness (Appendix 2, Tables 2.13A and 2.13B):

$$\sigma = 510 \times \text{HB} - 3605 \quad (2.25)$$

$$\sigma = 498 \times \text{HB} \quad (2.26)$$

Linear regression formula (2.25) provides 97.4–100% accuracy in calculating tensile strength. The correlation coefficient is 0.9962 (Appendix 2, Table 2.13A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (2.26) provides 97.2–100% accuracy in calculating tensile strength (Appendix 2, Table 2.13B). The use of the formulas is limited to Brinell hardness range of 190–365 HB.

1.2.4. Free-machining steels

Free-machining steels are divided into resulfurized group (AISI 11XX grades) and resulfurized and rephosphorized group (AISI 12XX grades).

Resulfurized group contains low-carbon and medium carbon grades. There are seven standard low-carbon grades (AISI 1108 to AISI 1119) and eight medium-carbon grades (AISI 1132 to AISI 1151). Resulfurized grades are produced to a range of 0.08–0.33% sulfur, which is much higher than that for 10XX series grades of carbon steels. Increased sulfur content improves machinability. Manganese content ranges from 0.30–1.65%, which is higher than that in the majority of other carbon steels. An increased amount of manganese provides better hardenability. AISI 11XX grades contain no more than 0.040% phosphorus, which is the same amount as in other carbon steels, except AISI 12XX grades.

The author studied the relationship between the tensile strength (σ) and Brinell hardness (HB) of the resulfurized grades for which sufficient number of data points were available. Linear regression analysis and statistical treatment of data were applied. As a result of this study, engineering formulas were developed to calculate tensile strength versus Brinell hardness for the following grades: AISI 1117, 1118, 1137, 1141, and 1144.

AISI 1117 grade is produced to a range of 0.14–0.20% C, 1.00–1.30% Mn, and 0.08–0.13% S (sulfur). Applications of this steel include medium duty shafts, distributor cams, camshafts, pins, studs, universal joints, and in instances where good machinability and case hardening are required. The average machinability rating is 90% at Brinell hardness range of (121–149) HB (Ref 8, p.49).

Mechanical Properties of Steel

Heat treatment of 1117 steel provides the following hardness (Ref 8, pp.49, 50):

- 121 HB when annealed
- 126–143 HB when normalized; hardness increases if the diameter of the workpiece decreases
- 131–163 HB when cold drawn at low temperature; hardness increases if the diameter of the workpiece decreases
- 149–235 HB when carburized, quenched in water, and tempered; hardness increases if the diameter of the workpiece decreases.

Surface hardness of a round workpiece after quenching in water is as follows (hardness decreases when diameter of the workpiece increases):

0.5 in. 42.0 HRC or 391 HB — converted by equation (1.16)

1.0 in. 37.0 HRC or 344 HB — converted by equation (1.15)

2.0 in. 33.0 HRC or 310 HB — converted by equation (1.14)

4.0 in. 32.0 HRC or 302 HB — converted by equation (1.14)

The following formulas were developed to calculate tensile strength of 1117 steel depending on Brinell hardness (Appendix 2, Tables 2.14A and 2.14B):

$$\sigma = 479 \times \text{HB} + 2674 \quad (2.27)$$

$$\sigma = 498 \times \text{HB} \quad (2.28)$$

Linear regression formula (2.27) provides 97.3–99.8% accuracy in calculating tensile strength. The correlation coefficient is 0.9937 (Appendix 2, Table 2.14A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (2.28) provides 96.7–99.7% accuracy in calculating tensile strength (Appendix 2, Table 2.14B). The use of the formulas is limited to Brinell hardness range of 110–185 HB.

AISI 1118 grade is produced to a range of 0.14–0.20% C, 1.30 to 1.60% Mn, and 0.08–0.13% S. Applications of this steel are similar to those described for AISI 1117 steel. The average machinability rating of this steel after cold drawn processing is 85% at 143 HB (Ref 8, p.5).

Heat treatment of this steel provides the following hardness (Ref 8, pp.49, 50):

- 131 HB when annealed
- 131–156 HB when normalized; hardness increases if the diameter of the workpiece decreases
- 131–163 HB when cold drawn at low temperature; hardness increases if the diameter of the workpiece decreases
- 156–285 HB when carburized, quenched in water, and tempered; hardness increases if the diameter of the workpiece decreases.

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Surface hardness of a round workpiece after quenching in water is as follows (hardness decreases when the diameter of the workpiece increases):

0.5 in. 43.0 HRC or 401 HB — converted by equation (1.16)

1.0 in. 36.0 HRC or 336 HB — converted by equation (1.15)

2.0 in. 34.0 HRC or 319 HB — converted by equation (1.14)

4.0 in. 32.0 HRC or 302 HB — converted by equation (1.14)

The following formulas were developed to calculate tensile strength of 1118 steel depending on Brinell hardness (Appendix 2, Tables 2.15A and 2.15B):

$$\sigma = 508 \times \text{HB} - 1619 \quad (2.29)$$

$$\sigma = 497 \times \text{HB} \quad (2.30)$$

Linear regression formula (2.29) provides 97.1–99.9% accuracy in calculating tensile strength. The correlation coefficient is 0.9983 (Appendix 2, Table 2.15A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (2.30) provides 97.1–99.8% accuracy in calculating tensile strength (Appendix 2, Table 2.15B). The use of the formulas is limited to Brinell hardness range of 110–285 HB.

AISI 1137 grade is produced to a range of 0.32–0.39% C, 1.35–1.65% Mn, and 0.08–0.13% S. This steel is most commonly used for spline shafts, studs, bolts, and nuts with machined threads. The average machinability rating of this steel is 70% at Brinell hardness range of (163–212) HB (Ref 8, p.58).

Heat treatment of 1137 steel provides the following hardness (Ref 8, p.57):

- 174 HB when annealed
- 192–201 HB when normalized; hardness slightly increases if the diameter of the workpiece decreases
- 192–255 HB when oil quenched and tempered; hardness increases if the diameter of the workpiece and tempering temperature decrease
- 197–262 HB when water quenched and tempered; hardness increases if the diameter of the workpiece and tempering temperature decrease.

Surface hardness of a round workpiece after quenching in oil:

0.5 in. 48.0 HRC or 456 HB — converted by equation (1.17)

1.0 in. 34.0 HRC or 319 HB — converted by equation (1.14)

2.0 in. 28.0 HRC or 272 HB — converted by equation (1.13)

4.0 in. 21.0 HRC or 231 HB — converted by equation (1.12)

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Surface hardness of a round workpiece after quenching in water:

0.5 in. 57.0 HRC or 596 HB — converted by equation (1.19)

1.0 in. 56.0 HRC or 577 HB — converted by equation (1.19)

2.0 in. 52.0 HRC or 512 HB — converted by equation (1.18)

4.0 in. 48.0 HRC or 456 HB — converted by equation (1.17)

The following formulas were developed to calculate tensile strength of 1137 steel depending on Brinell hardness (Appendix 2, Tables 2.16A and 2.16B):

$$\sigma = 486 \times \text{HB} + 1474 \quad (2.31)$$

$$\sigma = 493 \times \text{HB} \quad (2.32)$$

Linear regression formula (2.31) provides 97.2–100% accuracy in calculating tensile strength. The correlation coefficient is 0.9933 (Appendix 2, Table 2.16A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (2.32) provides 97.0–99.9% accuracy in calculating tensile strength (Appendix 2, Table 2.16B). The use of the formulas is limited to Brinell hardness range of 160–265 HB.

AISI 1141 grade is produced to a range of 0.37–0.45% C, 1.35–1.65% Mn, and 0.08–0.13% S. Applications of this steel include nuts, split rivets, machine screws, and wood screws. The average machinability rating is 70% at Brinell hardness range of (163–223) HB (Ref 8, p.59).

Heat treatment of 1141 steel provides the following hardness (Ref 8, p.61):

- 163 HB when annealed
- 201–207 HB when normalized; hardness slightly increases if the diameter of the workpiece decreases
- 183–262 HB when oil quenched and tempered; hardness increases if the diameter of the workpiece and tempering temperature decrease

Surface hardness of a round workpiece after quenching in oil is:

0.5 in. 52.0 HRC or 512 HB — converted by equation (1.18)

1.0 in. 48.0 HRC or 456 HB — converted by equation (1.17)

2.0 in. 36.0 HRC or 336 HB — converted by equation (1.15)

4.0 in. 27.0 HRC or 265 HB — converted by equation (1.13)

The following formulas were developed to calculate tensile strength of 1141 steel depending on Brinell hardness (Appendix 2, Tables 2.17A and 2.17B):

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$$\sigma = 475 \times \text{HB} + 5151 \quad (2.33)$$

$$\sigma = 500 \times \text{HB} \quad (2.34)$$

Linear regression formula (2.33) provides 97.2–100% accuracy in calculating tensile strength. The correlation coefficient is 0.9942 (Appendix 2, Table 2.17A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (2.34) provides 97.5–100% accuracy in calculating tensile strength (Appendix 2, Table 2.17B). The use of the formulas is limited to Brinell hardness range of 170–265 HB.

AISI 1144 grade is produced to a range of 0.40–0.48% C, 1.35–1.65% Mn, and 0.24–0.33% S. Typical applications of AISI 1144 steel include split rivets, machine and wood screws, and nuts. Addition of silicon in the amount of 0.15–0.30% and special heat treatment improve strength properties and produce fatigue-proof steel, which is used primarily for boring bar shanks. The average machinability rating of this steel is 80% at Brinell hardness range of (167–235) HB (Ref 8, p.60).

Heat treatment of 1144 steel provides the following hardness (Ref 8, p.61):

- 167 HB when annealed
- 192–201 HB when normalized; hardness slightly increases if the diameter of the workpiece decreases
- 183–235 HB when oil quenched and tempered; hardness increases if the diameter of the workpiece and tempering temperature decrease.

Surface hardness of a round workpiece after quenching in oil is:

0.5 in. 39.0 HRC or 362 HB — converted by equation (1.15)

1.0 in. 36.0 HRC or 336 HB — converted by equation (1.15)

2.0 in. 30.0 HRC or 286 HB — converted by equation (1.14)

4.0 in. 27.0 HRC or 265 HB — converted by equation (1.13)

The following formulas were developed to calculate tensile strength of 1144 steel depending on Brinell hardness (Appendix 2, Tables 2.18A and 2.18B):

$$\sigma = 452 \times \text{HB} + 8254 \quad (2.35)$$

$$\sigma = 493 \times \text{HB} \quad (2.36)$$

Linear regression formula (2.35) provides 97.8–99.8% accuracy in calculating tensile strength. The correlation coefficient is 0.9911 (Appendix 2, Table 2.18A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (2.36) provides 96.9–100% accuracy in calculating tensile strength (Appendix 2, Table 2.18B). The use of the formulas is limited to Brinell hardness range of 165–235 HB.

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Resulfurized and rephosphorized free-machining steels are produced to a range of 0.10–0.35% sulfur and 0.04–0.12% phosphorus in order to improve chip control and increase metal removal rate. The addition of lead in the amount of 0.15–0.35% reduces friction and the accumulation of heat between the cutting edge of the tool and the workpiece. There are five standard grades: AISI 1211, 1212, 1213, 1215, and 12L14. There are two nonstandard leaded grades: AISI 12L13 and 12L15. Leaded grades are most commonly used for high-speed screw machine products where the superior machining characteristics of these steels is fully utilized and a large amount of machining is necessary to produce finished parts. Machinability ratings are as follows: 95% at 163 HB (AISI 1211 grade), 100% at 167 HB (AISI 1212 grade), 135% at 167 HB (AISI 1213 grade), and 160% at 163 HB (AISI 12L14).

The author studied the relationship between the tensile strength and Brinell hardness of unleaded **AISI 1211, 1212, 1213, and 1215 steels**, for which only a few data points were available.

The following formulas for calculating tensile strength versus Brinell hardness were developed (Appendix 2, Tables 2.19A and 2.19B):

$$\sigma = 478 \times \text{HB} - 2354 \quad (2.37)$$

$$\sigma = 462 \times \text{HB} \quad (2.38)$$

Linear regression formula (2.37) provides 99.1–99.3% accuracy in calculating tensile strength. The correlation coefficient is 0.9988 (Appendix 2, Table 2.19A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (2.38) provides 98.4–99.8% accuracy in calculating tensile strength (Appendix 2, Table 2.19B). The use of the formulas is limited to Brinell hardness range of 120–170 HB.

1.2.5. Nonresulfurized high-manganese steels

Nonresulfurized high-manganese steels (AISI 1513 to AISI 1566) are produced to a range of 0.75–1.65% manganese. These grades are limited to 0.040% phosphorus and 0.050% sulfur. Currently, there are twelve standard grades, but mechanical properties were available only for two grades: AISI 1547 (1.35–1.65% Mn, 0.43–0.51 C) and AISI 1548 (1.10–1.40% Mn, 0.44–0.52 C).

AISI 1547 and 1548 grades are used where the increased carbon content (0.43–0.52%) is needed to improve wear characteristics, and where greater strength levels are required, but cannot be obtained by using other carbon steels with the same carbon content. The average machinability ratings are as follows (Ref 8, p.70):

- Cold drawn processing: AISI 1547 — 40% at 207 HB; AISI 1548 — 45% at 217 HB
- Annealed, cold drawn: AISI 1547 — 45% at 187 HB; AISI 1548 — 50% at 192 HB

The following formulas were developed to calculate tensile strength of these steels depending on their Brinell hardness (Appendix 2, Tables 2.20A and 2.20B):

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$$\sigma = 511 \times \text{HB} - 4240 \quad (2.39)$$

$$\sigma = 490 \times \text{HB} \quad (2.40)$$

Linear regression formula (2.39) provides 98.6–99.9% accuracy in calculating tensile strength. The correlation coefficient is 0.9919 (Appendix 2, Table 2.20A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (2.40) provides 98.5–99.9% accuracy in calculating tensile strength (Appendix 2, Table 2.20B). The use of the formulas is limited to Brinell hardness range of 190–220 HB.

Concluding Remarks on Carbon Steels

1. Carbon steels are divided into six groups: low-carbon steels, medium-carbon steels, and high-carbon steels; free-machining resulfurized steels; free-machining resulfurized and rephosphorized steels; and nonresulfurized high-manganese steels.

2. The average machinability ratings of steels are shown below:

Low-carbon steels — 75–50%

Medium-carbon steels — 70–45%

High-carbon steels — 60–45%

Free-machining 11XX steels — 100–65%

Free-machining 12XX steels — 160–100%

High-manganese steels — 65–40%

These ratings are based on AISI 1212 steel as 100% average machinability.

3. Currently, there are 77 standard grades of carbon steel, including:

16 grades of low-carbon steel

16 grades of medium-carbon steel

14 grades of high-carbon steel

14 grades of free-machining steel, AISI 11XX series

5 grades of free-machining steel, AISI 12XX series

12 grades of high-manganese steel

4. The study of the tensile strength – Brinell hardness relationships conducted by the author resulted in developing 20 statistical and 20 linear regression formulas. These formulas are listed in Table 1.2.

5. Strength-to-hardness ratios in statistical formulas for the majority of carbon steels range from 493 to 504. The strength-to-hardness ratio for high-manganese steels is 490 and the strength-

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to-hardness ratio for 12XX free-machining steels is 462. The high accuracy in calculating tensile strength is obtained through multiplication Brinell hardness number by appropriate strength-to-hardness ratio.

6. The correlation coefficients range from 0.9908–0.9988, indicating that linear regression formulas provide high accuracy in calculating tensile strength versus Brinell hardness.

7. The applications of statistical and linear regression formulas are limited to Brinell hardness ranges shown in this Table 1.2.

Table 1.2. Formulas for calculating tensile strength versus Brinell hardness

Categories of Carbon Steel	AISI Grades	Brinell hardness range, HB	Statistical Formula	Linear Regression Formula	Correlation Coefficient
Low-carbon steel	1015	100–220	$\sigma = 499 \times \text{HB}$	$\sigma = 468 \times \text{HB} + 4120$	0.9967
	1018	100–165	$\sigma = 496 \times \text{HB}$	$\sigma = 493 \times \text{HB} + 398$	0.9941
	1020	110–255	$\sigma = 497 \times \text{HB}$	$\sigma = 502 \times \text{HB} - 662$	0.9977
	1021, 1022	120–265	$\sigma = 502 \times \text{HB}$	$\sigma = 521 \times \text{HB} - 2962$	0.9971
	1025	100–145	$\sigma = 497 \times \text{HB}$	$\sigma = 485 \times \text{HB} + 1492$	0.9942
Medium-carbon steel	1030	125–190	$\sigma = 498 \times \text{HB}$	$\sigma = 471 \times \text{HB} + 4376$	0.9908
	1035	130–210	$\sigma = 498 \times \text{HB}$	$\sigma = 502 \times \text{HB} - 634$	0.9977
	1040	140–225	$\sigma = 493 \times \text{HB}$	$\sigma = 455 \times \text{HB} + 6954$	0.9936
	1045	160–200	$\sigma = 503 \times \text{HB}$	$\sigma = 567 \times \text{HB} - 11278$	0.9952
	1050	160–270	$\sigma = 498 \times \text{HB}$	$\sigma = 501 \times \text{HB} - 568$	0.9969
High-carbon steel	1060	175–305	$\sigma = 499 \times \text{HB}$	$\sigma = 513 \times \text{HB} - 3597$	0.9956
	1080	170–365	$\sigma = 504 \times \text{HB}$	$\sigma = 511 \times \text{HB} - 2109$	0.9969
	1095	190–365	$\sigma = 498 \times \text{HB}$	$\sigma = 510 \times \text{HB} - 3605$	0.9962
Free-machining steel	1117	110–185	$\sigma = 498 \times \text{HB}$	$\sigma = 479 \times \text{HB} + 2674$	0.9937
	1118	110–285	$\sigma = 497 \times \text{HB}$	$\sigma = 508 \times \text{HB} - 1619$	0.9983
	1137	160–265	$\sigma = 493 \times \text{HB}$	$\sigma = 486 \times \text{HB} + 1474$	0.9933
	1141	170–265	$\sigma = 500 \times \text{HB}$	$\sigma = 475 \times \text{HB} + 5151$	0.9942
	1144	165–235	$\sigma = 493 \times \text{HB}$	$\sigma = 452 \times \text{HB} + 8254$	0.9911
Free-machining steel	1211, 1212 1213, 1215	120–170	$\sigma = 462 \times \text{HB}$	$\sigma = 478 \times \text{HB} - 2354$	0.9988
High-manganese steel	1547 1548	190–220	$\sigma = 490 \times \text{HB}$	$\sigma = 511 \times \text{HB} - 4240$	0.9919

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1.3. Alloy Steels

In 1988 the United States produced 10.9 million tons of alloy steel, or 10.9% of total steel production (Ref 7, p.147). It was much less than carbon steel (86.9%), but when hardness, strength, and wear resistance of the machined parts are a necessity, the use of alloy steel is the right choice.

“Alloy steels constitute a category of ferrous materials that exhibit mechanical properties superior to carbon steels as the result of additions of such alloying elements as nickel, chromium, and molybdenum. Total alloy content can range from 2.0% up to levels just below that of stainless steels. For many alloy steels, the primary function of the alloying elements is to increase hardenability in order to optimize mechanical properties and toughness after heat treatment” (Ref 7, p. 149).

“Steel is considered an alloy steel when the maximum content range of alloying elements exceeds one or more of the following limits: 1.65% manganese, 0.60% silicon, or 0.60% copper. Also included in the recognized field of alloy steels are steels with a specified or required range or minimum quantity of the following elements: aluminum, boron, chromium, cobalt, niobium, molybdenum, nickel, titanium, tungsten, vanadium, zirconium, or any other element added to obtain a desired alloying effect” (Ref 8, p. 73).

AISI–SAE system of designations for alloy steels is similar to carbon steels. With four digits in the designation, the last two digits indicate carbon content in hundredths of a percent. In the chromium steels with five digits in the designation (high-carbon, electric-furnace, E50100, E51100, and E52100 grades), the last three digits indicate carbon content, which is 1.00% minimum. The letter B between the second and third digits denotes boron steel, to which a minimum of 0.0005% boron has been added. The letter H after the four digits indicates a grade of steel produced to prescribed hardenability limits. H-steels require a slight modification in the chemical composition of the conventional grade with the same AISI numerical designation. Currently, there are 66 standard grades of alloy steel (Ref 8, pp.73, 75).

The first two digits of a designation number define the principal alloying element or elements, which identify the following twelve categories of alloy steels (Ref 8, p. 76).

1. Manganese steels

13XX grades contain: 1.75 % Mn.

2. Nickel steels

23XX grades contain: 3.5% Ni

25XX grades contain: 5.0% Ni

3. Nickel-chromium steels

31XX grades contain: 1.25% Ni, 0.65 and 0.80% Cr

32XX grades contain: 1.75% Ni, 1.07% Cr

33XX grades contain: 3.5% Ni, 1.50 and 1.57% Cr

34XX grades contain: 3.00% Ni, 0.77% Cr

4. Molybdenum steels

40XX grades contain: 0.20 and 0.25% Mo

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44XX grades contain: 0.40 and 0.52% Mo

5. Chromium-molybdenum steels

41XX contains: 0.50, 0.80, and 0.95% Cr; 0.12, 0.20, 0.25, and 0.30% Mo

6. Nickel-molybdenum steels

46XX grades contain: 0.85 and 1.82% Ni, 0.20 and 0.25% Mo

48XX grades contain: 3.50% Ni, 0.25% Mo

7. Chromium steels

50XX grades contain: 0.27, 0.40, 0.50, and 0.65% Cr

51XX grades contain: 0.80, 0.87, 0.92, 0.95, 1.00, and 1.05% Cr

50XXX grades contain: 0.50% Cr

51XXX grades contain: 1.02% Cr

52XXX grades contain: 1.45% Cr

8. Chromium-vanadium steels

61XX grades contain: 0.60, 0.80, and 0.95% Cr; 0.10 and 0.15% V (minimum)

9. Nickel-chromium-molybdenum steels

43XX grades contain: 1.82% Ni, 0.50 and 0.80% Cr, 0.25% Mo

47XX grades contain: 1.05% Ni, 0.45% Cr, 0.20 and 0.35% Mo

81XX grades contain: 0.30% Ni, 0.45% Cr, 0.12% Mo

86XX grades contain: 0.55% Ni, 0.50% Cr, 0.20% Mo

87XX grades contain: 0.55% Ni, 0.50% Cr, 0.25% Mo

88XX grades contain: 0.55% Ni, 0.50% Cr, 0.35% Mo

93XX grades contain: 3.25% Ni, 1.20% Cr, 0.12% Mo

94XX grades contain: 0.45% Ni, 0.40% Cr, 0.12% Mo

97XX grades contain: 0.55% Ni, 0.20% Cr, 0.20% Mo

98XX grades contain: 1.00% Ni, 0.80% Cr, 0.25% Mo

10. Chromium-molybdenum-aluminum steels

71XX grades contain: 1.60% Cr, 0.35% Mo, 1.13% Al

11. Tungsten-chromium steels

72XX grades contain: 1.75% W, 0.75% Cr

12. Silicon steels

92XX grades contain: 1.40 and 2.00% Si, 0.00 and 0.65% Cr

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1.3.1. Manganese steels

There are four standard grades: AISI 1330, 1335, 1340, 1345; and four H-grades: AISI 1330H, 1335H, 1340H, and 1345H.

Standard manganese steels are produced to a range of 1.60–1.90% manganese, and H-grades are produced to a range of 1.45–2.05% manganese. All 13XX grades are limited to 0.15–0.30% silicon, 0.035% phosphorus, and 0.040% sulfur.

The author studied the relationship between the tensile strength (σ) and Brinell hardness (HB) of those grades for which sufficient number of data points were available. The author applied linear regression analysis and statistical treatment of data. As a result of this study, engineering formulas to calculate tensile strength in relationship with Brinell hardness were developed only for AISI 1340 and 1340H grades. Applications and mechanical properties of these grades are described below.

AISI 1340 and 1340H grades are available as hot rolled and cold finished bar for high-strength bolts, screws, cap screws, socket-head screws, recessed-head screws, and other machined components. The average machinability rating of these steels is 50% at Brinell hardness range of (183–241) HB (Ref 8, pp.83, 84).

Heat treatment of AISI 1340 and 1340H grades provides the following hardness:

- 207 HB when annealed
- (235–269) HB when normalized; hardness increases if the diameter of the workpiece decreases
- (212–285) HB when oil quenched and tempered; hardness increases if the diameter of the workpiece and tempering temperature decrease.

Surface hardness of a round workpiece after quenching in oil depends on its diameter. Hardness decreases if the diameter of the workpiece increases (Ref 8, p.84):

0.5 in. 58 HRC or 614 HB — converted by equation (1.19)

1.0 in. 57 HRC or 596 HB — converted by equation (1.19)

2.0 in. 39 HRC or 362 HB — converted by equation (1.15)

4.0 in. 32 HRC or 302 HB — converted by equation (1.14)

The following formulas were developed to calculate tensile strength of 1340 and 1340H steels depending on Brinell hardness (Appendix 3, Tables 3.1A and 3.1B):

$$\sigma = 494 \times \text{HB} - 1006 \quad (3.1)$$

$$\sigma = 490 \times \text{HB} \quad (3.2)$$

Linear regression formula (3.1) provides 97.4–100% accuracy in calculating tensile strength. The correlation coefficient is 0.9925 (Appendix 3, Table 3.1A), indicating a strong linear relationship between tensile strength and Brinell hardness.

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Statistical formula (3.2) provides 97.6–99.9% accuracy in calculating tensile strength (Appendix 3, Table 3.1B). The use of the formulas is limited to Brinell hardness range of 200–285 HB.

1.3.2. Nickel steels

There are two nonstandard grades of nickel steel: **AISI A2317** and **AISI A2515**. **AISI grade A2317** is a high-nickel, carburizing steel used for relatively small diameter (from 5 to 8 inches) machinery gears. AISI grade A2515 is also a high-nickel, carburizing steel used for machine parts that require a case of medium thickness. Applications of these grades are limited because of nickel content (Ref 8, pp. 88, 94).

AISI A2317 is produced to a range of 3.25–3.75% nickel, and AISI A2515 is produced to a range of 4.75–5.25% nickel. Both grades are limited to 0.040% sulfur and 0.040% phosphorus; they contain 0.40–0.60% manganese and 0.20–0.35% silicon.

Limited data on the mechanical properties of AISI A2317 and 2515 steels didn't allow developing linear regression and statistical formulas for calculating tensile strength in relationship with Brinell hardness.

1.3.3. Nickel-chromium steels

There are four nonstandard groups of nickel-chromium steels: AISI 31XX, 32XX, 33XX, and 34XX.

Limited technical information was available only for **AISI 3140 grade**, which contains 1.10–1.40% nickel and 0.55–0.75% chromium. This grade is limited to 0.040% phosphorus and 0.040% sulfur; it contains 0.70–0.90% manganese and 0.20–0.35% silicon (Ref 8, p.95).

AISI 3140 steel is available in hot rolled and cold finished bar for machining into components. Only two data points for Brinell hardness (197 HB and 262 HB) and two data points for tensile strength (100,000 psi and 129,000 psi respectively) were published for this grade (Ref 8, p.97). It was not enough data to develop formulas for calculating tensile strength versus Brinell hardness.

1.3.4. Molybdenum steels

Molybdenum steels include two groups of alloy steels defined as AISI 40XX grades and AISI 44XX grades.

AISI 40XX alloy steels include six standard grades: AISI 4023, 4024, 4027, 4028, 4037, 4047 and five H-grades: AISI 4027H, 4028H, 4037H, 4042H, and 4047H.

Unfortunately, complete technical information was available only for AISI 4027 steel. Therefore, mechanical properties, applications, and the tensile strength – Brinell hardness relationship described below relate to this steel.

AISI 4027 grade is a carburizing steel with low-to-medium hardenability in the core. This steel contains 0.20–0.30% molybdenum, 0.70–0.90% manganese, and 0.15–0.30% silicon. AISI 4027 is available as hot rolled and cold finished bar for machining parts. The average machinability rating is 70% at Brinell hardness range of (167–212) HB.

Heat treatment of AISI 4027 steel provides the following hardness:

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- 143 HB when annealed
- (156–179) HB when normalized; hardness increases if the diameter of the workpiece decreases
- (192–321) HB when water quenched and tempered; hardness increases if the diameter of the workpiece and tempering temperature decrease.

Surface hardness of a round workpiece after quenching in water depends on its diameter. Hardness decreases if the diameter of the workpiece increases (Ref 8, p.100):

0.57 in. 50 HRC or 480 HB — converted by equation (1.18)

1.0 in. 50 HRC or 480 HB — converted by equation (1.18)

2.0 in. 47 HRC or 443 HB — converted by equation (1.17)

4.0 in. 83 HRB or 156 HB — converted by equation (1.8)

Brinell hardness – tensile strength relationships for AISI 4027 grade are expressed by the following formulas (Appendix 3, Tables 3.2A and 3.2B):

$$\sigma = 457 \times \text{HB} + 8389 \quad (3.3)$$

$$\sigma = 491 \times \text{HB} \quad (3.4)$$

Linear regression formula (3.3) provides 98.4–99.8% accuracy in calculating tensile strength. The correlation coefficient is 0.9984 (Appendix 3, Table 3.2A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (3.4) provides 97.1–99.9% accuracy in calculating tensile strength (Appendix 3, Table 3.2B). The use of these formulas is limited to Brinell hardness range of 190–325 HB.

AISI 44XX steels include four nonstandard grades: 4419, 4419H, 4422, and 4427. Complete technical information was available only for AISI 4419 and 4419H steels. Therefore, mechanical properties, applications, and the tensile strength – Brinell hardness relationship described below relate to them.

AISI 4419 and 4419H grades are produced to a range of 0.45–0.60% molybdenum and 0.15–0.35% silicon. AISI 4419 grade contains 0.45–0.65% manganese and AISI 4419H grade contains 0.35–0.75% manganese. These grades are carburizing steels. They are suitable for use in tractor and automotive gears, piston pins, and universal crosses. Oil quenching produces satisfactory case hardness.

Heat treatment of AISI 4419 and 4419H grades produces the following hardness:

- 121 HB when annealed
- (143–149) HB when normalized; hardness slightly increases if the diameter of the workpiece decreases
- (170–217) HB when carburized, quenched in oil, and tempered; hardness increases when the

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diameter of the workpiece and tempering temperature decrease (Ref.8, p.137).

Surface hardness of a round workpiece quenched in oil decreases when the diameter of the workpiece increases (Ref 8, p.138):

0.57 in. 96 HRB or 214 HB — converted by equation (1.11)

1.0 in. 94 HRB or 203 HB — converted by equation (1.10)

2.0 in. 94 HRB or 203 HB — converted by equation (1.10)

4.0 in. 93 HRB or 198 HB — converted by equation (1.10)

The average machinability rating of AISI 4419 and 4419H steels is 65% at Brinell hardness range of (170–212) HB. Brinell hardness – tensile strength relationships for these steels are expressed by the following formulas (Appendix 3, Tables 3.3A and 3.3B):

$$\sigma = 486 \times \text{HB} + 726 \quad (3.5)$$

$$\sigma = 490 \times \text{HB} \quad (3.6)$$

Linear regression formula (3.5) provides 96.2–99.9% accuracy in calculating tensile strength. The correlation coefficient is 0.9900 (Appendix 3, Table 3.3A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (3.6) provides 96.0–100% accuracy in calculating tensile strength (Appendix 3, Table 3.3B). The use of the formulas is limited to Brinell hardness range of 140–245 HB.

1.3.5. Chromium-molybdenum steels

Chromium-molybdenum steels, which are designated as AISI 41XX, include nine standard grades: AISI 4118, 4130, 4137, 4140, 4142, 4145, 4147, 4150, and 4161, and nine respective H-grades with the same numeric characters. There are two nonstandard grades: AISI 4135 and 4135H.

Complete technical information was available for the following standard grades and respective H-grades: AISI 4118, 4418H, 4130, 4130H, 4140, 4140H, 4150, and 4150H. Mechanical properties, applications, and the tensile strength – Brinell hardness relationships are provided for these steels.

AISI 4118 and 4118H grades are carburizing steels with low-to-medium core hardenability and intermediate case hardenability. Both grades are produced to the same range of molybdenum (0.08–0.15%), but different range of chromium: 0.40–0.60% (AISI 4118) and 0.30–0.70% (AISI 4118H). They are used for automotive gears, piston pins, ball studs, and roller bearings. Average machinability rating of these grades is 60% at Brinell hardness range of (170–207) HB (Ref 8, p.105).

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Heat treatment of AISI 4118 and 4118H grades produces the following Brinell hardness (Ref 8 p.106):

- 137 HB when annealed
- (137–170) HB when normalized; hardness increases if the diameter of the workpiece decreases
- (187–293) HB when carburized, quenched in oil, and tempered; hardness increases when the diameter of the workpiece and tempering temperature decrease.

Surface hardness of a round workpiece quenched in oil decreases when the diameter of the workpiece increases:

0.57 in. 33.0 HRC or 310 HB — converted by equation (1.14)

1.0 in. 22.0 HRC or 237 HB — converted by equation (1.12)

2.0 in. 88.0 HRB or 175 HB — converted by equation (1.9)

4.0 in. 87.0 HRB or 171 HB — converted by equation (1.9)

Brinell hardness – tensile strength relationships for AISI 4118 and 4118H grades are expressed by the following formulas (Appendix 3, Tables 3.4A and 3.4B):

$$\sigma = 518 \times \text{HB} - 6112 \quad (3.7)$$

$$\sigma = 492 \times \text{HB} \quad (3.8)$$

Linear regression formula (3.7) provides 96.4–99.8% accuracy in calculating tensile strength. The correlation coefficient is 0.9986 (Appendix 3, Table 3.4A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (3.8) provides 97.3–99.6% accuracy in calculating tensile strength (Appendix 3, Table 3.4B). The use of the formulas is limited to Brinell hardness range of 170–355 HB.

AISI 4130 and 4130H grades are produced to the same range of molybdenum (0.15–0.25%), but different ranges of chromium: 0.80–1.10% (AISI 4130) and 0.75–1.20% (AISI 4130H). These steels have good hardenability, strength, wear resistance, toughness, and ductility (Ref 8, p.108).

Hardness of these steels depends on the heat treatment (Ref 8, p.109):

- 156 HB when annealed
- (163–217) HB when normalized; hardness increases if the diameter of the workpiece decreases
- (197–331) HB when quenched in water and tempered; lower tempering temperature and a smaller workpiece diameter result in higher hardness.

Surface hardness of a round workpiece quenched in water decreases when the diameter of the workpiece increases (Ref 8, p.109):

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0.5 in. 51.0 HRC or 496 HB — converted by equation (1.18)

1.0 in. 51.0 HRC or 496 HB — converted by equation (1.18)

2.0 in. 47.0 HRC or 443 HB — converted by equation (1.17)

4.0 in. 45.5 HRC or 426 HB — converted by equation (1.16)

AISI 4130 and 4130H steels are used for automotive connecting rods, engine mounting lugs, shafts, fittings, bushings, gears, axles, gas cylinders, hydraulic lines, and airframe components (Ref 7, p.431). The average machinability rating of these grades is 70% at Brinell hardness range of (187–229) HB (Ref 8, p.109).

Brinell hardness – tensile strength relationships for AISI 4130 and 4130H grades are expressed by the following formulas (Appendix 3, Tables 3.5A and 3.5B):

$$\sigma = 500 \times \text{HB} - 1206 \quad (3.9)$$

$$\sigma = 496 \times \text{HB} \quad (3.10)$$

Linear regression formula (3.9) provides 97.8–99.8% accuracy in calculating tensile strength. The correlation coefficient is 0.9994 (Appendix 3, Table 3.5A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (3.10) provides 98.0–99.9% accuracy in calculating tensile strength (Appendix 3, Table 3.5B). The use of these formulas is limited to Brinell hardness range of 190–450 HB.

AISI 4140 and 4140H grades are produced to the same range of molybdenum (0.15–0.25%), but different ranges of chromium: 0.80–1.10% (AISI 4140) and 0.75–1.20% (AISI 4140H). These steels have high hardenability; good fatigue, abrasion, and impact resistance; they can be nitrided for maximum wear and abrasion resistance. These grades are deep-hardening alloys suitable for severe applications characterized by fatigue, abrasion, impact, and high-temperature stresses in small and large sections (Ref 8, p.113).

Hardness of these steels depends on the heat treatment (Ref 8, p.114):

- 197 HB when annealed
- (241–302) HB when normalized; hardness increases if the diameter of the workpiece decreases
- (229–341) HB when quenched in oil and tempered. Lower tempering temperature and a smaller workpiece diameter result in higher hardness.

Surface hardness of a round workpiece quenched in oil decreases when the diameter of the workpiece increases:

0.5 in. 57.0 HRC or 596 HB — converted by equation (1.19)

1.0 in. 55.0 HRC or 560 HB — converted by equation (1.18)

2.0 in. 49.0 HRC or 469 HB — converted by equation (1.17)

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4.0 in. 36.0 HRC or 336 HB — converted by equation (1.15)

The average machinability rating of AISI 4140 and 4140H grades is 65% at Brinell hardness range of (187–229) HB.

AISI 4140 and 4140H steels are used for high-strength machine parts such as connecting rods, crankshafts, steering knuckles, axles, oil well drilling bits, piston rods, pump parts, high-pressure tubing, gears, flanges, collets, machine tool parts, tong jaws, wrenches, sprockets, studs, pinions, high-strength bolts, and cap screws (Ref 7, p.432). AISI 4140 grade is also used to fabricate the cutting tool holders and shanks.

Brinell hardness – tensile strength relationships for AISI 4140 and 4140H grades are expressed by the following formulas (Appendix 3, Tables 3.6A and 3.6B):

$$\sigma = 506 \times \text{HB} - 3456 \quad (3.11)$$

$$\sigma = 496 \times \text{HB} \quad (3.12)$$

Linear regression formula (3.11) provides 97.1–99.9% accuracy in calculating tensile strength. The correlation coefficient is 0.9991 (Appendix 3, Table 3.6A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (3.12) provides 97.2–99.7% accuracy in calculating tensile strength (Appendix 3, Table 3.6B). The use of these formulas is limited to Brinell hardness range of 190–580 HB.

AISI 4150 and 4150H grades are produced to the same range of molybdenum (0.15–0.25%), but different ranges of chromium: 0.80–1.10% (AISI 4150) and 0.75–1.20% (AISI 4150H). They provide deep hardenability with small loss in machinability. In the preheat-treated condition, these steels provide optimum strength and hardness. AISI 4150 grade is used to fabricate shanks for ball nose milling cutters. Being heat treated to 36–40 HRC, the shanks are machined to required dimensions. The shanks at such hardness range exhibit good wear resistant.

Hardness of these steels depends on the heat treatment (Ref 8, p.121):

- 197 HB when annealed
- (293–375) HB when normalized; hardness increases if the diameter of the workpiece decreases
- (255–375) HB when quenched in oil and tempered.

Lower tempering temperature and a smaller workpiece diameter result in higher hardness.

Surface hardness of a round workpiece quenched in oil decreases when the diameter of the workpiece increases (Ref 8, p.121):

0.5 in. 64.0 HRC or 722 HB — is beyond the accurate reading (Ref 9, p.110)

1.0 in. 62.0 HRC or 688 HB — is beyond the accurate reading (Ref 9, p.110)

2.0 in. 58.0 HRC or 614 HB — converted by equation (1.19)

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4.0 in. 47.0 HRC or 443 HB — converted by equation (1.17)

The average machinability rating of AISI 4150 and 4150H grades is 55% at Brinell hardness range of (187–241) HB.

Brinell hardness – tensile strength relationships for AISI 4150 and 4150H grades are expressed by the following formulas (Appendix 3, Tables 3.7A and 3.7B):

$$\sigma = 527 \times \text{HB} - 8977 \quad (3.13)$$

$$\sigma = 498 \times \text{HB} \quad (3.14)$$

Linear regression formula (3.13) provides 97.4–99.9% accuracy in calculating tensile strength. The correlation coefficient is 0.9958 (Appendix 3, Table 3.7A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (3.14) provides 97.4–99.9% accuracy in calculating tensile strength (Appendix 3, Table 3.7B). The use of these formulas is limited to Brinell hardness range of 255–375 HB.

1.3.6. Nickel-molybdenum steels

Nickel-molybdenum steels are designated as AISI 46XX and AISI 48XX grades.

AISI 46XX steels include three standard grades: 4615, 4620, and 4626, and two H-grades: 4620H and 4626H. A sufficient number of the Brinell hardness and tensile strength data were available only for AISI 4620 and 4620H grades. Therefore, mechanical properties and tensile strength – hardness relationship are described for these two grades.

AISI 4620 and 4620H grades are produced to the same range of molybdenum (0.20–0.30%), but different ranges of nickel: 1.65–2.00% (AISI 4620) and 1.55–2.00% (AISI 4620H). These grades are carburizing steels with intermediate case hardenability and medium core hardenability. They provide good core toughness and hardness penetration with minimum distortion.

The average machinability rating of these grades is 65% at Brinell hardness range of (183–229) HB (Ref 8, p.141).

Hardness of these steels depends on the heat treatment (Ref 8, p. 142):

- 149 HB when annealed
- (163–192) HB when normalized; hardness increases if the diameter of the workpiece decreases
- (170–255) HB when carburized, quenched in oil, and tempered. Lower tempering temperature and a smaller workpiece diameter result in higher hardness.

Surface hardness of a round workpiece quenched in oil decreases when the diameter of the workpiece increases:

0.5 in. 40.0 HRC or 371 HB — converted by equation (1.16)

1.0 in. 27.0 HRC or 265 HB — converted by equation (1.13)

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2.0 in. 24.0 HRC or 247 HB — converted by equation (1.12)

4.0 in. 96.0 HRB or 214 HB — converted by equation (1.11)

Brinell hardness – tensile strength relationships for AISI 4620 and 4620H grades are expressed by the following formulas (Appendix 3, Tables 3.8A and 3.8B):

$$\sigma = 462 \times \text{HB} + 7075 \quad (3.15)$$

$$\sigma = 494 \times \text{HB} \quad (3.16)$$

Linear regression formula (3.15) provides 97.4–99.9% accuracy in calculating tensile strength. The correlation coefficient is 0.9980 (Appendix 3, Table 3.8A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (3.16) provides 96.2–100% accuracy in calculating tensile strength (Appendix 3, Table 3.8B). The use of these formulas is limited to Brinell hardness range of 145–305 HB.

AISI 48XX steels include three standard grades: 4815, 4817, and 4820, and three respective H-grades with the same numeric characters. A sufficient number of Brinell hardness and tensile strength data were available only for AISI 4820 and 4820H grades. Therefore, mechanical properties and tensile strength–hardness relationship are described for these two grades.

AISI 4820 and 4820H grades are produced to a range of 0.20–0.30% molybdenum, but different ranges of nickel: 3.25–3.75% (AISI 4820) and 3.20–3.80% (AISI 4820H). These grades are carburizing steels with high hardenability in both the case and core. They are used for case hardened gears, bearings, and races.

The average machinability rating of these grades is 50% at Brinell hardness range of (187–229) HB (Ref 8, p.153).

Hardness of these steels depends on the heat treatment (Ref 8, pp.152, 153):

- 197 HB when annealed
- (212–235) HB when normalized; hardness increases if the diameter of the workpiece decreases
- (235–401) HB when carburized, quenched in oil, and tempered. Lower tempering temperature and a smaller work piece diameter result in higher hardness
- (401 – 415) HB when quenched in oil, tempered, and carburized.

Surface hardness of a round workpiece quenched in oil decreases when the diameter of the workpiece increases:

0.5 in. 45.0 HRC or 421 HB — converted by equation (1.16)

1.0 in. 43.0 HRC or 401 HB — converted by equation (1.16)

2.0 in. 36.0 HRC or 336 HB — converted by equation (1.15)

4.0 in. 27.0 HRC or 265 HB — converted by equation (1.13)

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Brinell hardness – tensile strength relationships for AISI 4820 and 4820H grades are expressed by the following formulas (Appendix 3, Tables 3.9A and 3.9B):

$$\sigma = 502 \times \text{HB} - 2994 \quad (3.17)$$

$$\sigma = 493 \times \text{HB} \quad (3.18)$$

Linear regression formula (3.17) provides 96.9–100% accuracy in calculating tensile strength. The correlation coefficient is 0.9990 (Appendix 3, Table 3.9A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (3.18) provides 97.3–100% accuracy in calculating tensile strength (Appendix 3, Table 3.9B). The use of these formulas is limited to Brinell hardness range of 195–415 HB.

1.3.7. Chromium steels

Chromium steels are defined as AISI 50XX, 51XX, E50100, E51100, and E52100.

AISI 50XX steels include two standard, but not commonly-produced grades such as AISI 5015 containing 0.30–0.50% chromium and AISI 5046 containing 0.20–0.35% chromium (Ref 7, p. 207).

There are four standard boron grades: AISI 50B44, 50B46, 50B50, and 50B60. AISI 50B46 grade is produced to a range of 0.20–0.35% chromium and the other three grades are produced to a range of 0.40–0.60% chromium. These grades are also available as H-steels. They are produced to a range of 0.0005–0.003% boron. Boron is added for increasing the depth of hardening when quenched.

AISI 50B50, 50B50H, 50B60, and 50B60H steels are used primarily for springs and hand tools.

The average machinability rating of AISI 50B50 and 50B50H is 55% at Brinell hardness range of (183–235) HB (Ref 8, p.165). The average machinability rating of AISI 5060, 50B60, and 50B60H is 55% at Brinell hardness range of (170–212) HB (Ref 8, p.167).

AISI 51XX steels include nine standard grades (AISI 5117 to AISI 5160) and one standard boron grade — AISI 51B60. These grades are also available as H-steels. Seven of these grades are produced to a range of 0.70–0.90% chromium. The other three grades are produced to various amounts of chromium: 0.80–1.10% (AISI 5130), 0.75–1.00% (AISI 5132), and 0.80–1.05% chromium (AISI 5135).

Detailed technical information on mechanical properties was available only for several AISI 51XX grades. Applications and formulas for calculating tensile strength versus Brinell hardness of these grades are described below.

AISI 5140 and 5140H grades contain various amount of chromium: 0.70–0.90% (AISI 5140) and 0.60–1.00% (AISI 5140H). These grades are used for bolts, cap screws, and recessed-head screws (Ref 8, p.172).

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Hardness of these steels depends on the heat treatment (Ref 8, p. 174):

- 167 HB when annealed
- (217–235) HB when normalized; hardness increases if the diameter of the workpiece decreases
- (217–302) HB when quenched in oil and tempered. Lower tempering temperature and a smaller workpiece diameter result in higher hardness.

Surface hardness of a round workpiece quenched in oil decreases when the diameter of the workpiece increases (Ref 8, p.174):

0.5 in. 57.0 HRC or 596 HB — converted by equation (1.19)

1.0 in. 53.0 HRC or 528 HB — converted by equation (1.18)

2.0 in. 46.0 HRC or 431 HB — converted by equation (1.17)

4.0 in. 35.0 HRC or 327 HB — converted by equation (1.14)

The average machinability rating of AISI 5140 and 5140H grades is 65% at Brinell hardness range of (179–217) HB.

Brinell hardness – tensile strength relationships for AISI 5140 and 5140H grades are expressed by the following formulas (Appendix 3, Tables 3.10A and 3.10B):

$$\sigma = 454 \times \text{HB} + 9955 \quad (3.19)$$

$$\sigma = 495 \times \text{HB} \quad (3.20)$$

Linear regression formula (3.19) provides 96.8–100% accuracy in calculating tensile strength. The correlation coefficient is 0.9902 (Appendix 3, Table 3.10A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (3.20) provides 96.8–99.7% accuracy in calculating tensile strength (Appendix 3, Table 3.10B). The use of these formulas is limited to Brinell hardness range of 165–305 HB.

AISI 5150 and 5150H grades are produced to different ranges of chromium: 0.70–0.90% (AISI 5150) and 0.60–1.00% (AISI 5150H). These grades are used mainly for coil springs, cone disc springs, and hand tools (Ref 8, p.175).

Hardness of AISI 5150 and 5150H alloy steels depends on the heat treatment conditions (Ref 8, p. 176):

- 197 HB when annealed
- (241–262) HB when normalized; hardness increases if the diameter of the workpiece decreases
- (235–311) HB when quenched in oil and tempered. Lower tempering temperature and a smaller workpiece diameter result in higher hardness.

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Surface hardness of a round workpiece quenched in oil decreases when the diameter of the workpiece increases:

0.5 in.	60.0 HRC or 653 HB — is beyond the accurate reading (Ref 9, p.111)
1.0 in.	59.0 HRC or 634 HB — is beyond the accurate reading (Ref 9, p.110)
2.0 in.	55.0 HRC or 560 HB — converted by equation (1.18)
4.0 in.	37.0 HRC or 344 HB — converted by equation (1.15)

The average machinability rating of AISI 5150 and 5150H steels is 60% at Brinell hardness range of (183–235) HB.

Brinell hardness – tensile strength relationships for AISI 5150 and 5150H grades are expressed by the following formulas (Appendix 3, Tables 3.11A and 3.11B):

$$\sigma = 536 \times \text{HB} - 9150 \quad (3.21)$$

$$\sigma = 500 \times \text{HB} \quad (3.22)$$

Linear regression formula (3.21) provides 98.3–100% accuracy in calculating tensile strength. The correlation coefficient is 0.9963 (Appendix 3, Table 3.11A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (3.22) provides 97.8–100% accuracy in calculating tensile strength (Appendix 3, Table 3.11B). The use of these formulas is limited to Brinell hardness range of 195–315 HB.

AISI 5160, 5160H, 51B60, and 51B60H grades contain different amounts of chromium. Standard grades (AISI 5160 and 51B60) are produced to a range of 0.70–0.90% Cr and two H-grades (AISI 5160H and 51B60H) are produced to a range of 0.60–1.00% Cr. These steels produce medium hardenability. The addition of boron improves hardenability of 51B60 and 51B60H grades by increasing the depth of hardening during quenching. All four grades are used for applications involving relatively small cross-sectional areas that are subject to severe service conditions, particularly for the fasteners, coil, and disc springs (Ref 8, p.178).

Hardness of these steels depends on the heat treatment (Ref 8, p.180):

- 197 HB when annealed
- (255–285) HB when normalized; hardness increases if the diameter of the workpiece decreases
- (241–341) HB when quenched in oil and tempered. Lower tempering temperature and a smaller workpiece diameter result in higher hardness.

Surface hardness of a round workpiece quenched in oil decreases when the diameter of the workpiece increases:

0.5 in.	63.0 HRC or 705 HB — is beyond the accurate reading (Ref 9, p.110)
1.0 in.	62.0 HRC or 688 HB — is beyond the accurate reading (Ref 9, p.110)

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2.0 in. 53.0 HRC or 528 HB — converted by equation (1.16)

4.0 in. 40.0 HRC or 371 HB — converted by equation (1.14)

The average machinability rating of AISI 5160, 5160H, 51B60, and 51B60H steels is 55% at Brinell hardness range of (179–217) HB (Ref 8, p.180).

Brinell hardness – tensile strength relationships for the above mentioned grades are expressed by the following formulas (Appendix 3, Tables 3.12A and 3.12B):

$$\sigma = 480 \times \text{HB} + 4511 \quad (3.23)$$

$$\sigma = 496 \times \text{HB} \quad (3.24)$$

Linear regression formula (3.23) provides 97.2–99.8% accuracy in calculating tensile strength. The correlation coefficient is 0.9917 (Appendix 3, Table 3.12A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (3.24) provides 97.0–99.7% accuracy in calculating tensile strength (Appendix 3, Table 3.12B). The use of these formulas is limited to Brinell hardness range of 240–345 HB.

AISI E50100, E51100, and E52100 grades are high-carbon, electric-furnace steels. The last three digits (100) indicate that these grades contain the same amount of carbon (the approximate middle of the carbon range is 1.00%). These steels are produced to different ranges of chromium: 0.40–0.60% (AISI E50100), 0.90–1.15% (AISI E51100), and 1.30–1.60% (AISI E51200). All three grades are produced to the same range of manganese (0.25–0.45%) and silicon (0.15–0.30%).

These steels are used primarily for ball and roller bearings. They are also suitable for other parts requiring high hardness and wear resistance. The average machinability rating of these steels is 40% at Brinell hardness range of (183–241) HB (Ref 8, p.155).

1.3.8. Chromium-vanadium steels

Chromium-vanadium steels are designated as AISI 61XX. There are two standard grades (AISI 6118 and 6150) and two H-grades (AISI 6118H and 6150H). Detailed technical information on mechanical properties was available only for AISI 6150 and 6150H grades. Applications and formulas for calculating tensile strength versus Brinell hardness of these two grades are described below.

AISI 6150 and 6150H grades contain 0.15% vanadium and different amounts of chromium: 0.80–1.10% (AISI 6150) and 0.75–1.20% (AISI 6150H). These grades are used for cone disc springs, coil springs, valve springs, piston rods, pump parts, and spline shafts (Ref 8, p.182).

Hardness of these steels depends on the heat treatment (Ref 8, p.184):

- 197 HB when annealed
- (255–285) HB when normalized; hardness increases if the diameter of the workpiece decreases
- (241–363) HB when quenched in oil and tempered. Lower tempering temperature and a

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smaller workpiece diameter result in higher hardness.

Surface hardness of a round workpiece quenched in oil decreases when the diameter of the workpiece increases (Ref 8, p.185):

0.5 in. 61.0 HRC or 670 HB — is beyond the accurate reading (Ref 9, p.110)

1.0 in. 60.0 HRC or 653 HB — is beyond the accurate reading (Ref 9, p.111)

2.0 in. 54.0 HRC or 544 HB — converted by equation (1.18)

4.0 in. 42.0 HRC or 391 HB — converted by equation (1.16)

The average machinability rating of these grades is 55% at Brinell hardness range of (183 – 241) HB.

Analysis of the hardness – tensile strength relationship resulted in developing the following formulas (Appendix 3, Tables 3.13A and 3.13B):

$$\sigma = 496 \times \text{HB} + 878 \quad (3.25)$$

$$\sigma = 499 \times \text{HB} \quad (3.26)$$

Linear regression formula (3.25) provides 96.4–99.9% accuracy in calculating tensile strength. The correlation coefficient is 0.9958 (Appendix 3, Table 3.13A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (3.26) provides 96.4–99.9% accuracy in calculating tensile strength (Appendix 3, Table 3.13B). The use of these formulas is limited to Brinell hardness range of 195–365 HB.

1.3.9. Nickel-chromium-molybdenum steels

Nickel-chromium-molybdenum category includes ten groups of alloy steels. AISI designations of these steels are listed on p.29. Each group is characterized by predetermined percentage of nickel, chromium, and molybdenum.

AISI 43XX alloy steels include three standard grades (AISI 4320, 4340, E4340) and three H-grades (AISI 4320H, 4340H, E4340H).

AISI 4320 and 4320H grades are produced to the same range of molybdenum (0.20 to 0.30%). AISI 4320 steel contains 1.65–2.00% nickel and 0.40–0.60% chromium. AISI 4320H steel contains 1.55–2.00% nickel and 0.35–0.65% chromium. Application of AISI 4320 and 4320H grades include tractor and automotive gears, piston pins, ball studs, universal crosses, and roller bearings (Ref 8, p.127).

Hardness of these steels depends on the heat treatment (Ref 8, pp.128, 129):

- 163 HB when annealed
- (201–248) HB when normalized; hardness increases if the diameter of the workpiece decreases

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- (241–415) HB when carburized, quenched in oil, and tempered. Lower tempering temperature and a smaller workpiece diameter result in higher hardness.

Surface hardness of a round workpiece quenched in oil decreases when the diameter of the workpiece increases (Ref 8, p.129):

0.5 in. 45.5 HRC or 426 HB — converted by equation (1.16)

1.0 in. 39.0 HRC or 362 HB — converted by equation (1.15)

2.0 in. 35.0 HRC or 327 HB — converted by equation (1.14)

4.0 in. 25.0 HRC or 253 HB — converted by equation (1.12)

The average machinability rating of AISI 4320 and 4320H grades is 60% at Brinell hardness range of (187–229) HB.

Brinell hardness – tensile strength relationships for AISI 4320 and 4320H grades are expressed by the following formulas (Appendix 3, Tables 3.14A and 3.14B):

$$\sigma = 499 \times \text{HB} - 774 \quad (3.27)$$

$$\sigma = 496 \times \text{HB} \quad (3.28)$$

Linear regression formula (3.27) provides 95.8–99.6% accuracy in calculating tensile strength. The correlation coefficient is 0.9957 (Appendix 3, Table 3.14A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (3.28) provides 95.8–99.5% accuracy in calculating tensile strength (Appendix 3, Table 3.14B). The use of these formulas is limited to Brinell hardness range of 160–430 HB.

AISI 4340 (E4340) steel is produced to a range of 1.65–2.00% nickel and 0.70–0.90% chromium. **AISI 4340H (E4340H) steel** is produced to a range of 1.55–2.00% nickel and 0.65–0.95% chromium. Both grades are produced to a range of 0.20–0.30% molybdenum. The letter E as a prefix indicates that the steel is made by electric furnace process. These steels are used in the production of piston pins, bearings, gears, machine tool arbors, die blocks, and cutting tool shanks.

Hardness of these steels depends on the heat treatment (Ref 8, p.132):

- 217 HB when annealed
- (321–363) HB when normalized; hardness increases if the diameter of the workpiece decreases
- (255–363) HB when oil quenched and tempered. Lower tempering temperature and a smaller workpiece diameter result in higher hardness.

Surface hardness of a round workpiece quenched in oil slightly decreases when the diameter

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of the workpiece increases:

0.5 in. 58.0 HRC or 614 HB — converted by equation (1.19)

1.0 in. 57.0 HRC or 596 HB — converted by equation (1.19)

2.0 in. 56.0 HRC or 577 HB — converted by equation (1.19)

4.0 in. 53.0 HRC or 528 HB — converted by equation (1.18)

The average machinability rating of these steels is 50% at Brinell hardness range of (187–241) HB.

Brinell hardness – tensile strength relationships for AISI 4340 and 4340H grades are expressed by the following formulas (Appendix 3, Tables 3.15A and 3.15B):

$$\sigma = 515 \times \text{HB} - 4322 \quad (3.29)$$

$$\sigma = 501 \times \text{HB} \quad (3.30)$$

Linear regression formula (3.29) provides 97.6–100% accuracy in calculating tensile strength. The correlation coefficient is 0.9974 (Appendix 3, Table 3.15A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (3.30) provides 97.1–99.9% accuracy in calculating tensile strength (Appendix 3, Table 3.15B). The use of these formulas is limited to Brinell hardness range of 215–365 HB.

AISI 47XX grades include one standard grade (AISI 4720), one nonstandard grade (AISI 4718), and two H-grades (4718H and 4720H).

AISI 4718 and 4718H grades are produced to a range of 0.30–0.40% molybdenum, but to different ranges of two other alloying elements: 0.90–1.20% nickel, 0.35–0.55% chromium (AISI 4718) and 0.85–1.25% nickel, 0.30–0.60% chromium (AISI 4718H). AISI 4718 and 4718H grades are carburizing steels with intermediate case hardenability and high core hardenability.

The average machinability rating of these grades is 60% at Brinell hardness range of (187–229) HB (Ref 8, p.146).

Brinell hardness – tensile strength relationships for AISI 4718 and 4718H grades are expressed by the following formulas (Appendix 3, Tables 3.16A and 3.16B):

$$\sigma = 558 \times \text{HB} - 26000 \quad (3.31)$$

$$\sigma = 483 \times \text{HB} \quad (3.32)$$

Linear regression formula (3.31) provides 98.6–99.9% accuracy in calculating tensile strength. The correlation coefficient is 0.9936 (Appendix 3, Table 3.16A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (3.32) provides 97.6–100% accuracy in calculating tensile strength

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(Appendix 3, Table 3.16B). The use of these formulas is limited to relatively narrow Brinell hardness range of 320–390 HB.

AISI 4720 and 4720H grades are produced to a range of 0.15–0.25% molybdenum, but to different ranges of two other alloying elements: 0.90–1.20% nickel, 0.35–0.55% chromium (AISI 4720) and 0.85–1.25% nickel, 0.30–0.60% chromium (AISI 4720H).

AISI 4720 and 4720H grades are carburizing steels with intermediate case hardenability and medium core hardenability. These steels are used for tractor and automotive gears, piston pins, universal crosses, and roller bearings (Ref 8, p.147).

The average machinability rating of these grades is 65% at Brinell hardness range of (187–229) HB (Ref 8, p.148).

AISI 86XX grades

AISI 86XX alloy steels include twelve standard grades (AISI 8615–8655), thirteen H-grades (AISI 8617H–8660H), two BH-grades (AISI 86B30H and 86B45H), and two B-grades (AISI 86B45 and 86B50).

The author studied the relationship between tensile strength and Brinell hardness of those grades for which a sufficient number of data points were available. The applications and related engineering formulas for calculating tensile strength versus Brinell hardness are provided for such grades.

AISI 8620 and 8620H grades are produced to a range of 0.15–0.25% molybdenum, but to different ranges of two other alloying elements: 0.40–0.70% nickel, 0.40–0.60% chromium (AISI 8620) and 0.35–0.75% nickel, 0.35–0.65% chromium (AISI 4620H).

AISI 8620 and 8620H grades are carburizing steels used in moderate section sizes, which require medium hardenability, strength, and shock resistance. Heat treatment depends on required hardness in the case and core for particular applications of parts. These grades are used for differential ring gears, camshafts, piston pins, transmission gears, steering worm gears, spline shafts, high-strength fasteners, and applications requiring medium strength, tough core properties, and hard wear-resistant case properties (Ref 8, p.189).

Hardness of these steels depends on the heat treatment (Ref 8, p.192):

- 149 HB when annealed
- (163–197) HB when normalized; hardness increases if the diameter of the workpiece decreases
- (201–388) HB when carburized, quenched in oil, and tempered. Lower tempering temperature and a smaller workpiece diameter result in higher hardness.

Surface hardness of a round workpiece quenched in oil decreases when the diameter of the workpiece increases:

0.5 in. 43.0 HRC or 401 HB — converted by equation (1.16)

1.0 in. 29.0 HRC or 279 HB — converted by equation (1.13)

2.0 in. 23.0 HRC or 242 HB — converted by equation (1.12)

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4.0 in. 22.0 HRC or 237 HB — converted by equation (1.12)

The average machinability rating of AISI grades 8620 and 8620H is 65% at Brinell hardness range of (179–235) HB.

Brinell hardness – tensile strength relationships for AISI 8620 and 8620H grades are expressed by the following formulas (Appendix 3, Tables 3.17A and 3.17B):

$$\sigma = 494 \times \text{HB} + 189 \quad (3.33)$$

$$\sigma = 495 \times \text{HB} \quad (3.34)$$

Linear regression formula (3.33) provides 97.8–99.9% accuracy in calculating tensile strength. The correlation coefficient is 0.9987 (Appendix 3, Table 3.17A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (3.34) provides 97.9–100% accuracy in calculating tensile strength (Appendix 3, Table 3.17B). The use of these formulas is limited to Brinell hardness range of 160–390 HB.

AISI 8630, 8630H, and 86B30H grades are produced to a range of 0.15–0.25% molybdenum, but to different ranges of two other alloying elements: 0.40–0.70% nickel, 0.40–0.60% chromium (AISI 8630) and 0.35–0.75% nickel, 0.35–0.65% chromium (AISI 8630H and 86B30H).

These steels are characterized by low hardenability, but the addition of 0.0005–0.003% boron enhances hardenability of AISI 86B30H grade. When normalized, they provide good mechanical properties. Applications of these grades include connecting rods, engine bolts, and studs (Ref 8, p.197).

Hardness of these steels depends on the heat treatment (Ref 8, p.199):

- 156 HB when annealed
- (187–201) HB when normalized; hardness increases if the diameter of the workpiece decreases
- (197–302) HB when quenched in water and tempered.

Lower tempering temperature and a smaller workpiece diameter result in higher hardness.

Surface hardness of a round workpiece quenched in water decreases when the diameter of the workpiece increases:

0.5 in. 52.0 HRC or 512 HB — converted by equation (1.18)

1.0 in. 52.0 HRC or 512 HB — converted by equation (1.18)

2.0 in. 51.0 HRC or 496 HB — converted by equation (1.18)

4.0 in. 47.0 HRC or 443 HB — converted by equation (1.17)

The average machinability rating of AISI 8630, 8630H, and 86B30H grades is 70% at Brinell

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hardness range of (179–229) HB.

Brinell hardness versus tensile strength of AISI 8630, 8630H, and 86B30H grades are expressed by the following formulas (Appendix 3, Tables 3.18A and 3.18B):

$$\sigma = 501 \times \text{HB} - 1373 \quad (3.35)$$

$$\sigma = 495 \times \text{HB} \quad (3.36)$$

Linear regression formula (3.35) provides 97.0–99.7% accuracy in calculating tensile strength. The correlation coefficient is 0.9948 (Appendix 3, Table 3.18A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (3.36) provides 97.1–99.6% accuracy in calculating tensile strength (Appendix 3, Table 3.18B). The use of these formulas is limited to Brinell hardness range of 185–305 HB.

AISI 8640 and 8640H grades are produced to a range of 0.15–0.25% molybdenum, but to different ranges of two other alloying elements: 0.40–0.70% nickel, 0.40–0.60% chromium (AISI 8640) and 0.35–0.75% nickel, 0.35–0.65% chromium (AISI 8640H).

AISI 8640 and 8640H grades are directly hardenable with medium hardenability. They are used for parts requiring a high degree of strength and toughness; for average-size automotive parts, such as steering knuckles, axle shafts, and propeller shafts; and for aircraft parts. Electric furnace grade E8640 is produced as aircraft quality, fine-grain steels, which are used in manufacturing cap, socket, and recessed-head aircraft screws (Ref 8, p.202).

Hardness of these steels depends on heat treatment (Ref 8, p.203):

- 277 HB at cold drawn processing
- (219–342) HB when quenched in oil and tempered. Lower tempering temperature and a smaller workpiece diameter result in higher hardness.

The average machinability rating of these grades is 65% at Brinell hardness range of (184–229) HB.

Brinell hardness – tensile strength relationships for AISI 8640 and 8640H grades are expressed by the following formulas (Appendix 3, Tables 3.19A and 3.19B):

$$\sigma = 454 \times \text{HB} + 11534 \quad (3.37)$$

$$\sigma = 494 \times \text{HB} \quad (3.38)$$

Linear regression formula (3.37) provides 97.8–99.8% accuracy in calculating tensile strength. The correlation coefficient is 0.9926 (Appendix 3, Table 3.19A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (3.38) provides 96.6–100% accuracy in calculating tensile strength (Appendix 3, Table 3.19B). The use of these formulas is limited to Brinell hardness range of 215–345 HB.

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AISI 8642 and 8642H grades are produced to a range of 0.15–0.25% molybdenum, but to different ranges of two other alloying elements: 0.40–0.70% nickel, 0.40–0.60% chromium (AISI 8642) and 0.35–0.75% nickel, 0.35–0.65% chromium (AISI 4642H). Mechanical properties, the applications, and machinability rating of these steels are similar to those described for AISI grades 8640 and 8640H.

Brinell hardness – tensile strength relationships for AISI 8642 and 8642H grades are expressed by the following formulas (Appendix 3, Tables 3.20A and 3.20B):

$$\sigma = 489 \times \text{HB} + 1737 \quad (3.39)$$

$$\sigma = 494 \times \text{HB} \quad (3.40)$$

Linear regression formula (3.39) provides 98.3–99.9% accuracy in calculating tensile strength. The correlation coefficient is 0.9988 (Appendix 3, Table 3.20A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (3.40) provides 98.4–99.9% accuracy in calculating tensile strength (Appendix 3, Table 3.20B). The use of these formulas is limited to Brinell hardness range of 235–365 HB.

AISI 8650, 8650H, and 86B50H grades are produced to a range of 0.15–0.25% molybdenum, but to different ranges of two other alloying elements: 0.40–0.70% nickel, 0.40–0.60% chromium (AISI 8650) and 0.35–0.75% nickel, 0.35–0.65% chromium (AISI 8650H and 86B50H).

These steels are directly hardenable with medium hardenability. The addition of 0.0005–0.003% boron enhances hardenability of AISI 86B50H grade. Primary applications include springs, hand tools, and automotive axle shafts (Ref 8, p.209).

Hardness of these steels depends on heat treatment (Ref 8, p.210):

- 212 HB when annealed
- (285–363) HB when normalized; hardness increases if the diameter of the workpiece decreases
- (241–363) HB when quenched in oil and tempered. Lower tempering temperature and a smaller workpiece diameter result in higher hardness.

Surface hardness of a round workpiece quenched in oil decreases when the diameter of the workpiece increases (Ref 8, p.211):

0.5 in. 61.0 HRC or 670 HB — is beyond the accurate reading (Ref 9, p.110)

1.0 in. 58.0 HRC or 614 HB — converted by equation (1.19)

2.0 in. 53.0 HRC or 528 HB — converted by equation (1.18)

4.0 in. 42.0 HRC or 391 HB — converted by equation (1.16)

The average machinability rating of AISI 8650, 8650H, and 86B50 grades is 60% at Brinell hardness range of (187–248) HB.

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Brinell hardness – tensile strength relationships for AISI 8650, 8650H, and 86B50 grades are expressed by the following formulas (Appendix 3, Tables 3.21A and 3.21B):

$$\sigma = 488 \times \text{HB} + 1743 \quad (3.41)$$

$$\sigma = 494 \times \text{HB} \quad (3.42)$$

Linear regression formula (3.41) provides 97.2–99.9% accuracy in calculating tensile strength. The correlation coefficient is 0.9947 (Appendix 3, Table 3.21A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (3.42) provides 97.1–100% accuracy in calculating tensile strength (Appendix 3, Table 3.21B). The use of these formulas is limited to Brinell hardness range of 210–365 HB.

AISI 87XX grades

There are two standard grades (AISI 8720 and 8740) and two H-grades (AISI 8720H and 8740H). Standard grades are produced to a range of 0.40–0.70% nickel, 0.40–0.60% chromium, and 0.20–0.30% molybdenum. H-grades are produced to a range of 0.35–0.75% nickel, 0.35–0.65% chromium, and 0.20–0.30% molybdenum.

AISI grades 8720 and 8720H are carburizing steels with medium-to-high case hardenability and medium core hardenability. These steels are used for gears, differential pinions, steering worms, wear-resistant pump parts, and spline shafts. The average machinability rating of these grades is 65% at Brinell hardness range of (179–235) HB (Ref. 8, p. 215).

AISI 8740 and 8740H grades are directly hardenable with medium hardenability. They are used for camshafts, wrist pins, clutch fingers, and other automotive parts. Other applications include torsion bars, springs, high-strength fasteners, and other cold headed parts (Ref 8, p.216).

Hardness of these steels depends on heat treatment (Ref 8, p.218):

- 201 HB when annealed
- (255–269) HB when normalized; hardness slightly increases if the diameter of the workpiece decreases
- (229–352) HB when quenched in oil and tempered. Lower tempering temperature and a smaller workpiece diameter result in higher hardness.

Surface hardness of a round workpiece quenched in oil decreases when the diameter of the workpiece increases:

- 0.5 in. 57.0 HRC or 596 HB — converted by equation (1.19)
- 1.0 in. 56.0 HRC or 577 HB — converted by equation (1.19)
- 2.0 in. 52.0 HRC or 512 HB — converted by equation (1.18)
- 4.0 in. 42.0 HRC or 391 HB — converted by equation (1.16)

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The average machinability rating of AISI grades 8740 and 8740H is 65% at Brinell hardness range of (184–235) HB.

Brinell hardness – tensile strength relationships for AISI 8740 and 8740H grades are expressed by the following formulas (Appendix 3, Tables 3.22A and 3.22B):

$$\sigma = 514 \times \text{HB} - 3411 \quad (3.43)$$

$$\sigma = 502 \times \text{HB} \quad (3.44)$$

Linear regression formula (3.43) provides 97.5–100% accuracy in calculating tensile strength. The correlation coefficient is 0.9937 (Appendix 3, Table 3.22A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (3.44) provides 97.2–100% accuracy in calculating tensile strength (Appendix 3, Table 3.22B). The use of these formulas is limited to Brinell hardness range of 200–355 HB.

AISI 88XX grades

There is one standard grade (**AISI 8822**) and one H-grade (**AISI 8820H**) in this group of nickel-chromium-molybdenum alloy steel.

AISI grades 8820 and 8820H are carburizing steels with medium-to-hard case hardenability and high core hardenability. They are used for heavy-duty, bevel-drive pinion and gears, and large roller bearings. The average machinability rating of these grades is 55% at Brinell hardness range of (179–223) HB (Ref 8, p.219).

AISI 93XX grades

There are two nonstandard grades in this group of nickel-chromium-molybdenum alloy steel: electric-furnace **AISI E9310** and **E9310H**. They are carburizing steels with high case and core hardenability; typical applications of these grades include aircraft gears and heavy-duty truck gears (Ref 8, p.223).

Hardness of these steels depends on heat treatment (Ref 8, p.225):

- 241 HB when annealed
- (255–285) HB when normalized; hardness increases if the diameter of the workpiece decreases
- (269–363) HB when carburized, quenched in oil, and tempered. Lower tempering temperature and a smaller workpiece diameter result in higher hardness.

Surface hardness of a round workpiece quenched in oil decreases when the diameter of the workpiece increases:

0.5 in. 40.0 HRC or 371 HB — converted by equation (1.16)

1.0 in. 40.0 HRC or 371 HB — converted by equation (1.16)

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2.0 in. 38.0 HRC or 353 HB — converted by equation (1.15)

4.0 in. 31.0 HRC or 294 HB — converted by equation (1.14)

The average machinability rating of AISI E9310 and E9310H grades is 50% at Brinell hardness range of (184–229) HB.

Brinell hardness – tensile strength relationships for AISI E9310 and E9310H grades are expressed by the following formulas (Appendix 3, Tables 3.23A and 3.23B):

$$\sigma = 479 \times \text{HB} + 3465 \quad (3.45)$$

$$\sigma = 490 \times \text{HB} \quad (3.46)$$

Linear regression formula (3.45) provides 97.9–99.9% accuracy in calculating tensile strength. The correlation coefficient is 0.9956 (Appendix 3, Table 3.23A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (3.46) provides 98.0–100% accuracy in calculating tensile strength (Appendix 3, Table 3.23B). The use of these formulas is limited to Brinell hardness range of 240–375 HB.

AISI 94XX grades

There are two standard boron grades: AISI 94B17 and 94B30 and five non-standard grades: AISI 94B15, 94B15H, 94B17H, 94B30H, and 94B40.

AISI grades 94B15, 94B15H, 94B17, and 94B17H are carburizing alloy steels with intermediate case and high core hardenability. The addition of 0.0005–0.003% boron improves machinability. These grades are used in manufacturing fasteners and cold headed parts that are quenched and tempered after forming. The average machinability rating of these grades is 70% at Brinell hardness range of (163–202) HB (Ref 8, pp.227, 228).

AISI grades 94B30, 94B30H, and 94B40 are directly hardenable with medium hardenability. The addition of 0.0005–0.003% boron improves depth of hardening for these grades.

The average machinability rating of AISI grades 94B30 and 94B30H is 70% at Brinell hardness range of (170–223) HB. These grades are used in manufacturing connecting rods, axle shafts, bolts, studs, screws, and other cold-headed parts, but not recommended for parts in high-temperature environments (Ref 8, p.229).

AISI 97XX grades

Mechanical properties of AISI 97XX alloy steels have not been published in “Engineering Properties of Steel” (Ref 8). Unfortunately, the author couldn’t find other publications related to mechanical properties and applications of this category of nickel-chromium-molybdenum alloy steels.

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AISI 98XX grades

This group of nickel-chromium-molybdenum steels is represented by **AISI 9840 grade**. This grade is produced to a range of 0.85–1.15% nickel, 0.70–0.90% chromium, and 0.20–0.30% molybdenum. It can be nitrided to improve wear and galling resistance or fatigue properties. Tensile strength and Brinell hardness data of AISI 9840 grade is limited to oil quenched condition (Ref 8, p. 233).

Brinell hardness – tensile strength relationship for AISI 9840 grade is expressed by the following formulas (Appendix 3, Tables 3.24A and 3.24B):

$$\sigma = 494 \times \text{HB} + 1591 \quad (3.47)$$

$$\sigma = 499 \times \text{HB} \quad (3.48)$$

Linear regression formula (3.47) provides 99.9–100% accuracy in calculating tensile strength. The correlation coefficient is 0.99997 (Appendix 3, Table 3.24A), indicating a very strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (3.48) provides 99.8–99.9% accuracy in calculating tensile strength (Appendix 3, Table 3.24B). The use of these formulas is limited to Brinell hardness range of 280–365 HB.

1.3.10. Chromium-molybdenum-aluminum steels

These alloy steels are designated as **AISI 71XX grades**. Unfortunately, the author couldn't find any technical information on mechanical properties of these grades and their use in manufacturing industry.

1.3.11. Tungsten-chromium steels

Tungsten-chromium steels are designated as **AISI 72XX grades**. Unfortunately, the author couldn't find any technical information on mechanical properties of these grades and their use in manufacturing industry.

1.3.12. Silicon steels

This category of alloy steels is designated as AISI 92XX and currently includes one standard AISI grade 9260 and two nonstandard grades: AISI 9255 and 9260H.

AISI 9255 and 9260 grades are produced to a range of 1.80–2.20% silicon, and 9260H grade is produced to a range of 1.70–2.20% silicon. These three grades are directly hardenable and widely used for springs subject to shock loads, moderately elevated temperature, and heavy-duty service.

The average machinability rating for AISI 9255 grade is 40% at Brinell hardness range of (179–229) HB, and for AISI 9260 grade is 40% at Brinell hardness range of (184–235) HB (Ref 8, pp.221, 223). Currently, technical information on mechanical properties is available only

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for AISI 9255 grade.

Hardness of this steel depends on heat treatment (Ref 8, p.221):

- 229 HB when annealed
- (269–277) HB when normalized; hardness slightly increases if the diameter of the workpiece decreases
- (262–331) HB when quenched in oil and tempered. Lower tempering temperature and a smaller workpiece diameter result in higher hardness.

Surface hardness of a round workpiece quenched in oil decreases when the diameter of the workpiece increases:

0.5 in. 61.0 HRC or 670 HB — is beyond the accurate reading (Ref 9, p.110)

1.0 in. 57.0 HRC or 596 HB — converted by equation (1.19)

2.0 in. 52.0 HRC or 512 HB — converted by equation (1.18)

4.0 in. 35.5 HRC or 331 HB — converted by equation (1.14)

Brinell hardness – tensile strength relationship for **AISI 9255 grade** is expressed by the following formulas (Appendix 3, Tables 3.25A and 3.25B):

$$\sigma = 567 \times \text{HB} - 17800 \quad (3.49)$$

$$\sigma = 504 \times \text{HB} \quad (3.50)$$

Linear regression formula (3.49) provides 98.4–100% accuracy in calculating tensile strength. The correlation coefficient is 0.9965 (Appendix 3, Table 3.25A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (3.50) provides 97.0–100% accuracy in calculating tensile strength (Appendix 3, Table 3.25B). The use of these formulas is limited to Brinell hardness range of 225–335 HB.

Concluding Remarks on Alloy Steels

1. Alloy steels are designated according to the AISI/SAE identification number and divided into twelve categories depending on the principal alloying elements. Currently, there are 66 standard grades of alloy steel.

2. Nickel-chromium-molybdenum alloy steel is the most versatile category. It includes ten groups, which differ one from another by content of the principal alloying elements. This category includes 22 standard grades.

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3. Machinability ratings of alloy steels vary from 40% (AISI 50100, 51100, and 51200 chromium, electric-furnace, alloy steel; AISI 9255 and 9260 silicon alloy steel) to 75% (AISI 4024 and 4028 molybdenum alloy steel) based on cold drawn AISI 1212 free-machining steel as 100% machinability rating.

4. The study of the tensile strength – Brinell hardness relationships conducted by the author, resulted in developing 25 statistical and 25 linear regression formulas. These formulas are summarized in Table 1.3.

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Table 1.3. Formulas for calculating tensile strength versus Brinell hardness

Category of Alloy Steel	AISI Grades	Brinell hardness range, HB	Statistical Formula	Linear Regression Formula	Correlation Coefficient
Manganese steel	1340, 1340H	200–285	$\sigma = 490 \times \text{HB}$	$\sigma = 494 \times \text{HB} - 1006$	0.9925
Molybdenum steel	4027	190–325	$\sigma = 491 \times \text{HB}$	$\sigma = 457 \times \text{HB} + 8389$	0.9984
Molybdenum steel	4419, 4419H	140–245	$\sigma = 490 \times \text{HB}$	$\sigma = 486 \times \text{HB} + 726$	0.9900
Chromium-molybdenum steel	4118, 4118H	170–355	$\sigma = 492 \times \text{HB}$	$\sigma = 518 \times \text{HB} - 6112$	0.9986
Chromium-molybdenum steel	4130, 4130H	190–450	$\sigma = 496 \times \text{HB}$	$\sigma = 500 \times \text{HB} - 1206$	0.9994
Chromium-molybdenum steel	4140, 4140H	190–580	$\sigma = 496 \times \text{HB}$	$\sigma = 506 \times \text{HB} - 3456$	0.9991
Chromium-molybdenum steel	4150, 4150H	255–375	$\sigma = 498 \times \text{HB}$	$\sigma = 527 \times \text{HB} - 8977$	0.9958
Nickel-molybdenum steel	4620, 4620H	145–305	$\sigma = 494 \times \text{HB}$	$\sigma = 462 \times \text{HB} + 7075$	0.9980
Nickel-molybdenum steel	4820, 4820H	195–415	$\sigma = 493 \times \text{HB}$	$\sigma = 502 \times \text{HB} - 2994$	0.9990
Chromium steel	5140, 5140H	165–305	$\sigma = 495 \times \text{HB}$	$\sigma = 454 \times \text{HB} + 9955$	0.9902
Chromium steel	5150, 5150H	195–315	$\sigma = 500 \times \text{HB}$	$\sigma = 536 \times \text{HB} - 9150$	0.9963
Chromium steel	5160, 5160H, 51B60, 51B60H	240–345	$\sigma = 496 \times \text{HB}$	$\sigma = 480 \times \text{HB} + 4511$	0.9917
Chromium-vanadium steel	6150, 6150H	195–365	$\sigma = 499 \times \text{HB}$	$\sigma = 496 \times \text{HB} + 878$	0.9958
Nickel-chromium-molybdenum steel	4320, 4320H	160–430	$\sigma = 496 \times \text{HB}$	$\sigma = 499 \times \text{HB} - 774$	0.9957

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Table 1.3 contined

Category of Alloy Steel	AISI Grades	Brinell hardness range, HB	Statistical Formula	Linear Regression Formula	Correlation Coefficient
Nickel-chromium-molybdenum steel	4340, 4340H, E4340, E4340H	215–365	$\sigma = 501 \times \text{HB}$	$\sigma = 515 \times \text{HB} - 4322$	0.9974
Nickel-chromium-molybdenum steel	4718, 4718H	320–390	$\sigma = 483 \times \text{HB}$	$\sigma = 558 \times \text{HB} - 26000$	0.9936
Nickel-chromium-molybdenum steel	8620, 8620H	160–390	$\sigma = 495 \times \text{HB}$	$\sigma = 494 \times \text{HB} + 189$	0.9987
Nickel-chromium-molybdenum steel	8630, 8630H, 86B30H	185–305	$\sigma = 495 \times \text{HB}$	$\sigma = 501 \times \text{HB} - 1373$	0.9948
Nickel-chromium-molybdenum steel	8640, 8640H	215–345	$\sigma = 494 \times \text{HB}$	$\sigma = 454 \times \text{HB} + 11534$	0.9926
Nickel-chromium-molybdenum steel	8642, 8642H	235–365	$\sigma = 494 \times \text{HB}$	$\sigma = 489 \times \text{HB} + 1737$	0.9988
Nickel-chromium-molybdenum steel	8650, 8650H, 86B50H	210–365	$\sigma = 494 \times \text{HB}$	$\sigma = 488 \times \text{HB} + 1743$	0.9947
Nickel-chromium-molybdenum steel	8740, 8740H	200–355	$\sigma = 502 \times \text{HB}$	$\sigma = 514 \times \text{HB} - 3411$	0.9937
Nickel-chromium-molybdenum steel	E9310, E9310H	240–375	$\sigma = 490 \times \text{HB}$	$\sigma = 479 \times \text{HB} + 3465$	0.9956
Nickel-chromium-molybdenum steel	9840	280–365	$\sigma = 499 \times \text{HB}$	$\sigma = 494 \times \text{HB} + 1591$	0.99997
Silicon steel	9255	225–335	$\sigma = 504 \times \text{HB}$	$\sigma = 567 \times \text{HB} - 17800$	0.9965

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5. Strength-to-hardness ratios in statistical formulas for the majority of alloy steels are ranging from 490 to 504. The strength-to-hardness ratio for AISI grades 4718 and 4718H of nickel-chromium-molybdenum steel is 483. The high accuracy in calculating tensile strength is obtained by multiplying the Brinell hardness number by the appropriate strength-to-hardness ratio.

6. The correlation coefficients range from 0.9900–0.99997, indicating that linear regression formulas provide high accuracy in calculating tensile strength versus Brinell hardness.

7. The applications of statistical and linear regression formulas are limited to Brinell hardness ranges shown in this table.

1.4. Stainless Steels

In 1988 the United States produced 2.2 million tons of stainless steel, or 2.2% of total steel production (Ref 7, p.147). It was less than alloy steel (10.9%), but when corrosion resistance and mechanical properties of the parts are the most important factors, the use of stainless steels is a necessity.

“Stainless steels are iron-base alloys containing at least 10.5% chromium. They achieve their stainless characteristics through the formation of adherent chromium oxide surface film. This oxide forms and heals itself in the presence of oxygen. Other elements added to improve particular characteristics, include nickel, molybdenum, copper, titanium, aluminum, silicon, niobium, nitrogen, sulfur, and selenium. Carbon is normally present in the amounts ranging from less than 0.03% to over 1.0% in certain martensitic grades” (Ref 7, p.841).

Original discoveries and developments in stainless steel technology began in England and Germany about 1910. The commercial production of stainless steels in the United States began in the 1920s by Allegheny, Carpenter, Firth-Sterling, U.S. Steel, and some other companies (Ref 7, p.841).

Stainless steels are divided into five groups: austenitic, martensitic, ferritic, duplex (ferritic-austenitic), and precipitation-hardening stainless steels.

Stainless steels are designated by AISI (the American Iron and Steel Institute) and by UNS (Unified Numbering System) differently.

The designation of AISI is a three-digit number and a numeric-letter code. The first numeral in a three-digit number identifies a group of stainless steels: the austenitic types are “2xx” and “3xx”; the martensitic and ferritic types are “4xx”; and the precipitation-hardening types are “6xx.” Precipitation-hardening types are also designated by letters PH, a two-digit number indicating percentage of chromium content, followed by a single-digit number indicating percentage of nickel content. The two-digit number and a single-digit number are separated with a hyphen.

The UNS designation consists of the letter S (assigned to stainless steel), followed by five digits. Austenitic types are S2xxxx and S3xxxx; martensitic and ferritic types are S4xxxx; precipitation-hardening types are S1xxxx.

1.4.1. Austenitic stainless steels

The term *austenitic* pertains to *austenite*, which is a solid solution of one or more elements in

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face-centered cubic iron. Unless otherwise designated (such as nickel austenite), the solute is generally assumed to be carbon. In this type of steel, austenite is stable at room temperature as a result of alloying. Austenite can dissolve up to 2.11% carbon. Austenite is relatively soft, ductile, and nonmagnetic.

The majority of austenitic steels are low in carbon (0.03–0.10%) and certain grades are produced to a range of 0.20–0.25% carbon. Chromium content varies from 15 to 26% and nickel content generally varies from 8 to 22%. AISI Types 3xx grades are produced to 2% manganese and AISI Types 2xx grades are produced to a range of 5.5–15.5% manganese. Currently, there are 29 standard austenitic steel grades.

The author studied the relationship between the tensile strength (σ) and Brinell hardness (HB) of those grades for which sufficient number of data points were available. The author applied linear regression analysis and statistical treatment of data. As a result of this study, engineering formulas to calculate tensile strength in relationship with Brinell hardness were developed. The formulas, applications, and mechanical properties of these grades are described below.

AISI Type 201 (UNS S20100) grade

AISI type 201 is chromium-nickel-manganese stainless steel produced to a range of 16–18% chromium, 3.5–5.5% nickel, and 5.5–7.5% manganese. The maximum content of other elements is as follows: 1.0% silicon, 0.25% nitrogen, 0.06% phosphorus, 0.03% sulfur, and 0.15% carbon. This grade resists corrosion attack over relatively long periods of exposure in both industrial and marine atmospheres. Applications of AISI type 201 include railroad and subway cars, truck trailers, automotive trim, window frames and doors, cooking ware, such as pans and lids. The average machinability rating of this steel is 45% compared to 100% for AISI 1212 free-machining steel (Ref 8, p.246).

Hardness of AISI type 201 steel depends on the heat treatment (Ref 8, p.247):

Annealed	87.0 HRB or 171 HB — converted by equation (1.9)
25% hard	25.0 HRC or 253 HB — converted by equation (1.12)
50% hard	32.0 HRC or 302 HB — converted by equation (1.14)
75% hard	37.0 HRC or 344 HB — converted by equation (1.15)
Full hard	41.0 HRC or 381 HB — converted by equation (1.16)
Extra hard	43.0 HRC or 401 HB — converted by equation (1.16)

Brinell hardness – tensile strength relationships for AISI type 201 stainless steel are expressed by the following formulas (Appendix 4, Tables 4.1A and 4.1B):

$$\sigma = 606 \times \text{HB} - 31737 \quad (4.1)$$

$$\sigma = 512 \times \text{HB} \quad (4.2)$$

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Linear regression formula (4.1) provides 92.9–99.2% accuracy in calculating tensile strength. The correlation coefficient is 0.9637 (Appendix 4, Table 4.1A), indicating a strong enough linear relationship between tensile strength and Brinell hardness.

Statistical formula (4.2) provides 91.2–99.4% accuracy in calculating tensile strength (Appendix 4, Table 4.1B). The use of these formulas is limited to Brinell hardness range of 250–405 HB.

AISI Type 301 (UNS S30100) grade

AISI type 301 is chromium-nickel stainless steel produced to a range of 16–18% chromium, 6.0–8.0% nickel, and 2.0% manganese. The maximum content of other elements is as follows: 1.0% silicon, 0.045% phosphorus, 0.030% sulfur, and 0.15% carbon. This grade exhibits excellent resistance to atmospheric corrosion in the annealed or cold worked condition. Applications of this steel include automobile wheel covers, aircraft and missile structures, transportation equipment, storm door frames, kitchen utensils, and tableware. The average machinability rating of this steel is 45% compared to 100% for AISI 1212 free-machining steel (Ref 8, p.253).

Hardness of AISI type 301 steel depends on the heat treatment (Ref 8, p.255):

Annealed 85.0 HRB or 163 HB — converted by equation (1.8)

25% hard 25.0 HRC or 253 HB — converted by equation (1.12)

50% hard 30.0 HRC or 286 HB — converted by equation (1.14)

75% hard 35.0 HRC or 327 HB — converted by equation (1.14)

Full hard 40.0 HRC or 371 HB — converted by equation (1.16)

Extra hard 43.0 HRC or 401 HB — converted by equation (1.16)

Brinell hardness – tensile strength relationships for AISI type 301 stainless steel are expressed by the following formulas (Appendix 4, Tables 4.2A and 4.2B):

$$\sigma = 609 \times \text{HB} - 27508 \quad (4.3)$$

$$\sigma = 525 \times \text{HB} \quad (4.4)$$

Linear regression formula (4.3) provides 93.2–98.8% accuracy in calculating tensile strength. The correlation coefficient is 0.9756 (Appendix 4, Table 4.2A), indicating a strong enough linear relationship between tensile strength and Brinell hardness.

Statistical formula (4.4) provides 93.6–99.9% accuracy in calculating tensile strength (Appendix 4, Table 4.2B), which is slightly more accurate than formula (4.3). The use of these formulas is limited to Brinell hardness range of 250–405 HB.

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AISI Types 302 and 302B (UNS S30200 and S30215) grades

AISI types 302 and 302B are chromium-nickel stainless steels. Both grades are produced to a range of 17–19% chromium, 8.0–10.0% nickel, and 2.0% manganese. The maximum content of other elements is: 0.045% phosphorus, 0.030% sulfur, and 0.15% carbon. But silicon content is different: AISI type 302 steel contains 1.0% and type 302B steel contains 2–3% (Ref 8, pp.258, 262).

The corrosion resistance of AISI type 302 steel is superior to that of type 301. This stainless steel has good resistance to many acidic environments, especially nitric acid, but has poor resistance to halogen acids. Applications of AISI type 302 include food processing machinery, hospital equipment, camera parts, aircraft cowling, furnace parts, steam and oil piping, nitric acid vessels, springs, and screens. The average machinability rating of this steel is 45% compared to 100% for AISI 1212 free-machining steel (Ref 8, p.258).

The resistance to scaling of AISI type 302B steel is superior to that of type 302. AISI type 302B is used primarily for parts exposed to high temperatures. The average machinability rating of 302B grade is 40% compared to 100% for AISI 1212 free-machining steel (Ref 8, p.262).

Brinell hardness – tensile strength relationships for AISI types 302 and 302B steels are expressed by the following formulas (Appendix 4, Tables 4.3A and 4.3B):

$$\sigma = 353 \times \text{HB} + 35507 \quad (4.5)$$

$$\sigma = 557 \times \text{HB} \quad (4.6)$$

Linear regression formula (4.5) provides 96.7–99.9% accuracy in calculating tensile strength. The correlation coefficient is 0.9873 (Appendix 4, Table 4.3A), indicating a strong enough linear relationship between tensile strength and Brinell hardness.

Statistical formula (4.6) provides 88.7–99.1% accuracy in calculating tensile strength (Appendix 4, Table 4.3B), which is less accurate than formula (4.5). The use of these formulas is limited to Brinell hardness range of 145–255 HB.

AISI Types 304, 304N, and 304HN (UNS S30400, S30451, and S30452) grades

AISI types 304, 304N, and 304HN are chromium-nickel stainless steels produced to the same content of chromium (18–20%), nickel (8.0–10.5%), manganese (2.0%), silicon (1.0%), carbon (0.08%), phosphorus (0.045%), and sulfur (0.030%). AISI types 304N (0.10–0.16% nitrogen) and 304HN (0.16–0.30% nitrogen) are high-nitrogen versions of type 304. The nitrogen provides higher yield strength and tensile strength in annealed types 304N and 304HN than in conventional type 304 and does not adversely affect ductility and corrosion resistance.

Applications of AISI type 304 stainless steel include machined shafts, dairy equipment, homogenizers, and valves and accessories for chemical handling equipment. The average machinability rating of this steel is about 60% compared to 100% for AISI 1212 free-machining steel (Ref 8, p.273).

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Applications of AISI types 304N and 304HN stainless steel include aircraft and aerospace components, marine shafting, pump parts, pressure vessels, heat exchangers, and parts for high-temperature service. The average machinability rating of these steels is about the same as for type 304 steel (Ref 8, p.280).

Brinell hardness – tensile strength relationships for AISI 304, 304N, and 304HN steels are expressed by the following formulas (Appendix 4, Tables 4.4A and 4.4B):

$$\sigma = 325 \times \text{HB} + 35246 \quad (4.7)$$

$$\sigma = 502 \times \text{HB} \quad (4.8)$$

Linear regression formula (4.7) provides 95.5–99.8% accuracy in calculating tensile strength. The correlation coefficient is 0.9842 (Appendix 4, Table 4.4A), indicating a strong enough linear relationship between tensile strength and Brinell hardness.

Statistical formula (4.8) provides 87.0–99.6% accuracy in calculating tensile strength (Appendix 4, Table 4.4B), which is less accurate than formula (4.7). The use of these formulas is limited to Brinell hardness range of 145–310 HB.

AISI Type 308 (UNS S30800) grade

AISI type 308 is a high-chromium, high-nickel stainless steel produced to a range of 19–21% chromium, 10–12% nickel, and 2.0% manganese. The maximum content of other elements is: 1.0% silicon, 0.045% phosphorus, 0.030% sulfur, and 0.08% carbon. The higher chromium and nickel content increases corrosion and heat resistance of this grade. Applications of AISI type 308 steel include: welding rod, industrial furnaces, and equipment for handling sulfite liquor at elevated temperatures (Ref 8, p.283).

Hardness of AISI Type 308 stainless steel at cold drawn condition depends on the diameter of the specimen: lower hardness numbers relate to 0.38-in.-diameter and higher hardness numbers relate to 0.13-in.-diameter specimens (Ref 8, p.284):

25% hard 23.0 HRC or 242 HB — converted by equation (1.12)

25% hard 28.0 HRC or 272 HB — converted by equation (1.13)

50% hard 29.0 HRC or 279 HB — converted by equation (1.13)

50% hard 32.0 HRC or 302 HB — converted by equation (1.14)

75% hard 33.0 HRC or 310 HB — converted by equation (1.14)

75% hard 37.0 HRC or 344 HB — converted by equation (1.15)

Full hard 38.0 HRC or 353 HB — converted by equation (1.15)

Full hard 43.0 HRC or 401 HB — converted by equation (1.16)

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Brinell hardness – tensile strength relationships for AISI type 308 steel are expressed by the following formulas (Appendix 4, Tables 4.5A and 4.5B):

$$\sigma = 695 \times \text{HB} - 61198 \quad (4.9)$$

$$\sigma = 499 \times \text{HB} \quad (4.10)$$

Linear regression formula (4.9) provides 95.6–99.1% accuracy in calculating tensile strength. The correlation coefficient is 0.9920 (Appendix 4, Table 4.5A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (4.10) provides 91.0–99.5% accuracy in calculating tensile strength (Appendix 4, Table 4.5B), which is slightly less accurate than formula (4.9). The use of these formulas is limited to Brinell hardness range of 240–405 HB.

AISI Types 316, 316L, 316F, and 316N (UNS S31600, S31603, S31620, and S31651) grades

All these grades are chromium-nickel-molybdenum stainless steels produced to the same amount of chromium (16–18%), nickel (10–14%), manganese (2.0%), and silicon (1.0%). AISI type 316F grade contains less molybdenum (1.75–2.00%) than the other three grades (2–3%), but more phosphorus (0.20%) and sulfur (0.10%) in comparison with 0.045% phosphorus and 0.030% sulfur in three other grades. AISI type 316L is a very low-carbon (0.03%) grade in comparison with three other grades, which contain 0.08% carbon. AISI type 316N is produced to a range of 0.10–0.16% nitrogen, which provides improved resistance against pitting and crevice corrosion.

Applications of these grades include:

AISI type 316 — chemical storage and transportation tanks; food processing equipment; digesters and evaporators for the paper industry; textile dyeing equipment; nuclear fuel cladding and heat exchangers; oil refining equipment. The machinability rating of this grade is 55% of that for AISI 1212 free-machining carbon steel (Ref 8, p.292).

AISI type 316L — pulp-handling equipment, equipment for production of rayon, rubber, and textile bleaches, high-temperature equipment. The machinability rating of this grade is 55% of that for AISI 1212 free-machining carbon steel (Ref 8, pp.296, 297).

AISI type 316F — automatic screw machine parts, and similar equipment for which AISI types 316 and 316L grades are used. Type 316F has a machinability rating 65% of that for AISI 1212 free-machining carbon steel (Ref 8, p.299).

AISI type 316N — chemical handling accessories and similar equipment for which the three other grades are used.

Brinell hardness – tensile strength relationships for the above listed grades are expressed by the following formulas (Appendix 4, Tables 4.6A and 4.6B):

$$\sigma = 231 \times \text{HB} + 47879 \quad (4.11)$$

$$\sigma = 536 \times \text{HB} \quad (4.12)$$

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Linear regression formula (4.11) provides 95.0–99.8% accuracy in calculating tensile strength. A correlation coefficient is 0.9030 (Appendix 4, Table 4.6A), indicating a strong enough linear relationship between tensile strength and Brinell hardness.

Statistical formula (4.12) provides 88.4–99.8% accuracy in calculating tensile strength (Appendix 4, Table 4.6B), which is less accurate than formula (4.11). The use of these formulas is limited to Brinell hardness range of 140–190 HB.

AISI Type 321 (UNS S32100) grade

AISI type 321 is a titanium-bearing, chromium-nickel stainless steel produced to a range of 17–19% chromium, 9.0–12.0% nickel, and 2.0% manganese. The maximum content of other elements is as follows: 1.0% silicon, 0.045% phosphorus, 0.030% sulfur, 0.08% carbon, and 0.40% titanium. The carbon combines with titanium to form titanium carbide, and leaves the chromium in solution to maintain full corrosion resistance.

Applications of AISI type 321 stainless steel include furnace parts, aircraft collector rings and exhaust parts, expansion joints, and high-temperature chemical handling equipment. The machinability rating of this steel is 45% of that for AISI 1212 free-machining carbon steel (Ref 8, p.304).

Brinell hardness – tensile strength relationships for AISI type 321 stainless steel are expressed by the following formulas (Appendix 4, Tables 4.7A and 4.7B):

$$\sigma = 339 \times \text{HB} + 32879 \quad (4.13)$$

$$\sigma = 534 \times \text{HB} \quad (4.14)$$

Linear regression formula (4.13) provides 97.6–99.4% accuracy in calculating tensile strength. The correlation coefficient is 0.9564 (Appendix 4, Table 4.7A), indicating a strong enough linear relationship between tensile strength and Brinell hardness.

Statistical formula (4.14) provides 94.2–99.5% accuracy in calculating tensile strength (Appendix 4, Table 4.6B), which is slightly less accurate than formula (4.13). The use of these formulas is limited to Brinell hardness range of 150–185 HB.

AISI Types 347 and 348 (UNS S34700 and S34800) grades

AISI types 347 and 348 are chromium-nickel stainless steels produced to the same amount of nickel (9–13%), manganese (2.0%), silicon (1.0%), phosphorus (0.045%), sulfur (0.030%), and carbon (0.080%). Chromium content is different: AISI type 347 steel has 17% and AISI type 348 steel has 19%. Both grades contain niobium and tantalum in the amount of 0.80% each. The additions of these two elements eliminate carbide precipitation and, consequently, intergranular corrosion.

Applications of AISI types 347 and 348 include aircraft exhaust parts, firewalls, pressure vessels, heavy welded equipment, and the elevated temperature chemical handling equipment. The machinability rating of these grades is 45% of that for AISI 1212 free-machining carbon steel (Ref 8, p.311).

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Brinell hardness – tensile strength relationships for AISI types 347 and 348 steels are expressed by the following formulas (Appendix 4, Tables 4.8A and 4.8B):

$$\sigma = 156 \times \text{HB} + 67234 \quad (4.15)$$

$$\sigma = 517 \times \text{HB} \quad (4.16)$$

Linear regression formula (4.15) provides 97.5–99.8% accuracy in calculating tensile strength. The correlation coefficient is 0.9213 (Appendix 4, Table 4.8A), indicating a strong enough linear relationship between tensile strength and Brinell hardness.

Statistical formula (4.16) provides 88.7–92.5% accuracy in calculating tensile strength (Appendix 4, Table 4.8B), which is less accurate than formula (4.15). The use of these formulas is limited to Brinell hardness range of 160–215 HB.

1.4.2. Martensitic stainless steels

The term martensitic pertains to martensite — an angular needlelike brittle micro-structure that is formed during rapid cooling of austenite at the temperature rate higher than 500 °F (260 °C) per second. Such rapid cooling causes restructuring of crystalline lattice of austenite into crystalline lattice of ferrite, in which only 0.04 percent carbon can be dissolved. The excessive amount of carbon transforms into a supersaturated solution of carbon in ferrite. This type of solution is called martensite, which is characterized by high hardness (greater than 60 HRC) and very low toughness. Therefore, steels that are quenched to martensite are also tempered, or heated, to some temperature below 1340 °F (727 °C).

Martensitic steels contain chromium as the major alloying element in the amount of 11.5–18.0 percent. The other elements are: manganese (1.0–1.25%), silicon (0.50–1.0%), phosphorus (0.04–0.06%), and sulfur (0.03–0.15%). Some martensitic steels also contain one or more of the following alloying elements: nickel, molybdenum, tungsten, vanadium, and selenium. Currently, there are 12 standard martensitic stainless steel grades.

The author studied the relationship between the tensile strength (σ) and Brinell hardness (HB) of those grades for which a sufficient number of data points were available. The author applied linear regression analysis and statistical treatment of data. As a result of this study, engineering formulas to calculate tensile strength in relationship with Brinell hardness were developed. The formulas, applications, and mechanical properties of these grades are described below.

AISI Type 403 (UNS S40300) grade

AISI type 403 is hardenable chromium stainless steel containing 11.5–13.0% chromium, 1.0% manganese, 0.50% silicon, and 0.15% carbon. This steel is resistant to the corrosive action of the atmosphere, fresh water and steam, mild acids, and alkalis. Application of AISI type 403 steel include steam turbine blades and parts, gas turbine blades and jet engine parts, furnace and valve parts, and burners operating below 1200 °F (650 °C). The machinability rating of this steel is 55% of that for AISI 1212 free-machining carbon steel (Ref 8, p.318).

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Brinell hardness – tensile strength relationships for AISI type 403 steel are expressed by the following formulas (Appendix 4, Tables 4.9A and 4.9B):

$$\sigma = 536 \times \text{HB} - 7792 \quad (4.17)$$

$$\sigma = 492 \times \text{HB} \quad (4.18)$$

Linear regression formula (4.17) provides 99.0–99.7% accuracy in calculating tensile strength. The correlation coefficient is 0.9994 (Appendix 4, Table 4.9A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (4.18) provides 97.4–100% accuracy in calculating tensile strength (Appendix 4, Table 4.9B), which is, practically, as accurate as formula (4.17). The use of these formulas is limited to Brinell hardness range of 145–225 HB.

AISI Type 414 (UNS S41400) grade

AISI type 414 is hardenable, chromium-nickel stainless steel containing 11.5–13.5% chromium, 1.25–2.50% nickel, 1.0% manganese, 1.0% silicon, and 0.15% carbon. This steel resists corrosion from atmosphere, fresh water, steam, many petroleum products, ammonia, and mild acid environments. AISI type 414 grade is not recommended for high-temperature service. It will discolor at about 450 °F (230 °C), but scale does not form until the temperature exceeds 1200 °F (650 °C). Applications of this steel include mining equipment, shafts, spindles, valve seats, gage parts, scraper knives, fasteners, scissors, and beater bars. The machinability rating of AISI type 414 steel is about 45% of that for AISI 1212 free-machining carbon steel (Ref 8, p.332).

Brinell hardness – tensile strength relationships for AISI type 414 steel are expressed by the following formulas (Appendix 4, Tables 4.10A and 4.10B):

$$\sigma = 513 \times \text{HB} - 4350 \quad (4.19)$$

$$\sigma = 499 \times \text{HB} \quad (4.20)$$

Linear regression formula (4.19) provides 93.8–99.3% accuracy in calculating tensile strength. The correlation coefficient is 0.9952 (Appendix 4, Table 4.10A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (4.20) provides 94.8–100% accuracy in calculating tensile strength (Appendix 4, Table 4.10B), which is, practically, as accurate as formula (4.19). The use of these formulas is limited to Brinell hardness range of 225–430 HB.

AISI Types 416 and 416Se (UNS S41600 and S41623) grades

AISI types 416 and 416Se are hardenable, chromium stainless steels produced to a range of 12–14% chromium, 1.25% manganese, 1.0% silicon, 0.06% phosphorus, and 0.15% carbon. AISI

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type 416 steel contains 0.15% sulfur (five times more than that for the majority of martensitic stainless steels), and AISI type 416Se steel contains 0.15% selenium. Sulfur or selenium is added to improve machinability rating, which is about 90% of that for AISI 1212 free-machining carbon steel. Applications of these grades include shafts and pumps components, valve and appliance parts, studs, hardware, and automobile trim (Ref 8, pp.337, 338).

Brinell hardness – tensile strength relationships for AISI types 416 and 416Se steels are expressed by the following formulas (Appendix 4, Tables 4.11A and 4.11B):

$$\sigma = 527 \times \text{HB} - 9448 \quad (4.21)$$

$$\sigma = 492 \times \text{HB} \quad (4.22)$$

Linear regression formula (4.21) provides 94.9–99.4% accuracy in calculating tensile strength. The correlation coefficient is 0.9936 (Appendix 4, Table 4.11A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (4.22) provides 94.8–100% accuracy in calculating tensile strength (Appendix 4, Table 4.11B), which is, practically, as accurate as formula (4.21). The use of these formulas is limited to Brinell hardness range of 150–370 HB.

AISI Type 420 (UNS S42000) grade

AISI type 420 is hardenable, chromium stainless steel produced to a range of 12–14% chromium, 1.0% manganese, 1.0% silicon, 0.04% phosphorus, 0.03% sulfur, and 0.15% carbon. Applications of this steel include hand tools, dental and surgical instruments, valve trim and parts, shafts, and molds for plastics. The machinability rating is 50% of that for AISI 1212 free-machining carbon steel (Ref 8, p.344).

Brinell hardness – tensile strength relationships for AISI type 420 steel are expressed by the following formulas (Appendix 4, Tables 4.12A and 4.12B):

$$\sigma = 498 \times \text{HB} - 1193 \quad (4.23)$$

$$\sigma = 494 \times \text{HB} \quad (4.24)$$

Linear regression formula (4.23) provides 99.0–99.9% accuracy in calculating tensile strength. The correlation coefficient is 0.9999 (Appendix 4, Table 4.12A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (4.24) provides 98.6–99.9% accuracy in calculating tensile strength (Appendix 4, Table 4.12B), which is, practically, as accurate as formula (4.23). The use of these formulas is limited to Brinell hardness range of 190–600 HB.

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AISI Type 431 (UNS S43100) grade

AISI type 431 is hardenable, chromium-nickel stainless steel containing 15–17% chromium, 1.25–2.50% nickel, 1.0% manganese, 1.0% silicon, 0.03% sulfur, 0.04% phosphorus, and 0.20% carbon. This grade is heat treatable to obtain high hardness and strength combined with excellent toughness. It is resistant to the corrosive action from the atmosphere, various alkalis, and mild acids. This steel has better resistance to corrosion from marine atmosphere than other martensitic stainless steels. It also has good oxidation resistance up to about 1500 °F (815 °C) in continuous service. The machinability rating of AISI type 431 steel is about 45% of that for AISI 1212 free-machining carbon steel (Ref 8, p.356).

Brinell hardness – tensile strength relationships for AISI type 431 steel are expressed by the following formulas (Appendix 4, Tables 4.13A and 4.13B):

$$\sigma = 553 \times \text{HB} - 18263 \quad (4.25)$$

$$\sigma = 498 \times \text{HB} \quad (4.26)$$

Linear regression formula (4.25) provides 96.8–99.6% accuracy in calculating tensile strength. The correlation coefficient is 0.9939 (Appendix 4, Table 4.13A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (4.26) provides 95.5–99.2% accuracy in calculating tensile strength (Appendix 4, Table 4.13B), which is, practically, as accurate as formula (4.25). The use of these formulas is limited to Brinell hardness range of 260–425 HB.

AISI Type 440A (UNS S44002) grade

AISI type 440A is a high-chromium (16–18%) and high-carbon (0.60–0.75%) stainless steel, which contains molybdenum (0.75%), manganese (1.0%), silicon (1.0%), phosphorus (0.04%), and sulfur (0.03%). This grade provides good corrosion resistance to many industrial and domestic environments. Optimum corrosion resistance is obtained in the as-hardened condition or with a temper below 800 °F (425 °C). Applications of this steel include pivot pins, valve parts, dental and surgical instruments, and cutlery. The machinability rating of this grade is about 45% of that for AISI 1212 free-machining carbon steel (Ref 8, p.358).

Brinell hardness – tensile strength relationships for AISI type 440A steel are expressed by the following formulas (Appendix 4, Tables 4.14A and 4.14B):

$$\sigma = 524 \times \text{HB} - 7353 \quad (4.27)$$

$$\sigma = 499 \times \text{HB} \quad (4.28)$$

Linear regression formula (4.27) provides 97.3–100% accuracy in calculating tensile strength. The correlation coefficient is 0.9996 (Appendix 4, Table 4.14A), indicating a strong linear relationship between tensile strength and Brinell hardness.

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Statistical formula (4.28) provides 95.9–99.3% accuracy in calculating tensile strength (Appendix 4, Table 4.14B), which is slightly less accurate than formula (4.27). The use of these formulas is limited to Brinell hardness range of 205–510 HB.

AISI Type 440B (UNS S44003) grade

AISI type 440B is a high-chromium (16–18%) and high-carbon (0.75–0.95%) stainless steel, which contains molybdenum (0.75%), manganese (1.0%), silicon (1.0%), phosphorus (0.04%), and sulfur (0.03%). Corrosion resistance of this grade is similar to AISI type 440A. Optimum corrosion resistance is obtained with a temper below 800 °F (425 °C). Applications of AISI type 440B include bearings, spatula blades, food processing knives, hardened balls, and cutlery. The machinability rating of this grade is about 40% of that for AISI 1212 free-machining carbon steel (Ref 8, p.363).

Brinell hardness – tensile strength relationships for AISI type 440B steel are expressed by the following formulas (Appendix 4, Tables 4.15A and 4.15B):

$$\sigma = 511 \times \text{HB} - 3677 \quad (4.29)$$

$$\sigma = 499 \times \text{HB} \quad (4.30)$$

Linear regression formula (4.29) provides 98.8–100% accuracy in calculating tensile strength. The correlation coefficient is 0.9999 (Appendix 4, Table 4.15A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (4.30) provides 98.1–99.8% accuracy in calculating tensile strength (Appendix 4, Table 4.15B), which is, practically, as accurate as formula (4.29). The use of these formulas is limited to Brinell hardness range of 210–555 HB.

AISI Type 440C (UNS S44004) grade

AISI type 440C is a high-chromium (16–18%) and high-carbon (0.95–1.20%) stainless steel, which contains molybdenum (0.75%), manganese (1.0%), silicon (1.0%), phosphorus (0.04%), and sulfur (0.03%). With heat treatment, this steel acquires the highest hardness of any type of corrosion-resistant or heat-resistant steel. AISI type 440C steel resists corrosion in a normal domestic environment and very mild industrial environments, including many petroleum products and organic materials. This grade is always used in the hardened and tempered condition. Optimum corrosion resistance is obtained by hardening from 2000 °F (1095 °C) to obtain better carbide solution. Applications of AISI type 440C include bearing balls and races, needle valves, ball check valves, valve seats, pump parts, bushings, cutlery, and wear-resistant textile machine components. The machinability rating of this grade is about 40% of that for AISI 1212 free-machining carbon steel (Ref 8, p.365).

Brinell hardness – tensile strength relationships for AISI type 440C steel are expressed by the following formulas (Appendix 4, Tables 4.16A and 4.16B):

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$$\sigma = 488 \times \text{HB} + 1674 \quad (4.31)$$

$$\sigma = 493 \times \text{HB} \quad (4.32)$$

Linear regression formula (4.31) provides 97.2–99.9% accuracy in calculating tensile strength. The correlation coefficient is 0.9995 (Appendix 4, Table 4.16A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (4.32) provides 97.4–99.7% accuracy in calculating tensile strength (Appendix 4, Table 4.16B), which is, practically, as accurate as formula (4.31). The use of these formulas is limited to Brinell hardness range of 220–580 HB.

1.4.3. Ferritic stainless steels

The term *ferritic* pertains to *ferrite* – a solid solution of one or more elements in body-centered cubic iron. Unless otherwise designated, for instance, as chromium ferrite, the solute is generally assumed to be carbon. Not more than 0.04% carbon can be dissolved in ferrite. Ferrite is stable below 1670 °F (910 °C); it is soft and highly ductile. The magnetic property of ferrite is stable below 1414 °F (768 °C).

Ferritic steels contain chromium as the major alloying element in the amount of 10.5–27.0 percent. Carbon content varies from 0.025 to 0.20%. Four standard elements are: manganese (1.0–1.5%), silicon (1.0%), phosphorus (0.04–0.06%), and sulfur (0.03–0.15%). Some grades of ferritic steels may contain nickel, molybdenum, aluminum, titanium, niobium, and selenium as alloying elements. Currently, there are 12 standard ferritic grades, which are used for their corrosion resistance and resistance to scaling at elevated temperatures, rather than for high-strength purposes. High-temperature strengths of ferritic grades are relatively poor compared to the austenitic grades.

The author studied the relationship between the tensile strength (σ) and Brinell hardness (HB) of those grades for which sufficient number of data points were available. The author applied linear regression analysis and statistical treatment of data. As a result of this study, engineering formulas to calculate tensile strength in relationship with Brinell hardness were developed. The formulas, applications, and mechanical properties of these grades are described below.

AISI Type 405 (UNS S40500) grade

AISI type 405 is a nonhardening stainless steel containing 11.5–14.5% chromium, four standard alloying elements mentioned above, and 0.08% carbon. A small addition of aluminum (0.10–0.30%) blocks formation of austenite at high temperature so that hardening does not occur upon quenching. This grade provides good corrosion resistance and oxidation resistance up to about 1200 °F (650 °C) in applications when high strength of hardenable grades is not required. Applications of this grade include quenching racks, vessel linings, and precision rolled profiles for steam turbine parts. The average machinability rating of AISI type 405 is about 55% of that for AISI 1212 free-machining carbon steel (Ref 8, p.324).

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Brinell hardness – tensile strength relationships for AISI type 405 stainless steel are expressed by the following formulas (Appendix 4, Tables 4.17A and 4.17B):

$$\sigma = 410 \times \text{HB} + 7905 \quad (4.33)$$

$$\sigma = 461 \times \text{HB} \quad (4.34)$$

Linear regression formula (4.33) provides 93.7–99.2% accuracy in calculating tensile strength. The correlation coefficient is 0.9467 (Appendix 4, Table 4.17A), indicating a strong enough linear relationship between tensile strength and Brinell hardness.

Statistical formula (4.34) provides 94.0–99.7% accuracy in calculating tensile strength (Appendix 4, Table 4.17B), which is, practically, as accurate as formula (4.33). The use of these formulas is limited to Brinell hardness range of 130–185 HB.

AISI Types 430, 434, 435, and 436 (UNS: S43000, S43400, S43500, and S43600) grades

All four grades are produced to the same range of chromium (14–18%), the major alloying element; manganese (1.0%), silicon (1.0%), carbon (0.12%), phosphorus (0.04%), and sulfur (0.03%). Some grades contain molybdenum, and niobium plus tantalum.

AISI type 430 is straight chromium grade with excellent corrosion resistance. It is widely used for chemical handling equipment, appliances, and decorative trim. The machinability of this grade is 55% of that for AISI 1212 free-machining carbon steel.

AISI type 434 grade contains an addition of molybdenum (0.75–1.25%) for increased corrosion resistance and improved resistance to pitting from various chemicals.

AISI type 435 grade contains niobium plus tantalum (0.40–0.60%), which enhances resistance to roping, i.e. separating or dividing.

AISI type 436 grade contains the molybdenum addition of type 434 and addition of niobium plus tantalum (0.40–0.60%). As a result of these additions, type 436 stainless steel exhibits heat and corrosion resistance with minimum roping tendency when compared to AISI type 430 grade.

Applications of these four grades include oil burner parts, tank cars, automotive trim, appliance parts, and nitric acid storage tanks (Ref 8, pp.353, 354).

Brinell hardness – tensile strength relationships for the above-mentioned four grades are expressed by the following formulas (Appendix 4, Tables 4.18A and 4.18B):

$$\sigma = 431 \times \text{HB} + 5810 \quad (4.35)$$

$$\sigma = 466 \times \text{HB} \quad (4.36)$$

Linear regression formula (4.35) provides 96.8–99.7% accuracy in calculating tensile strength. The correlation coefficient is 0.9708 (Appendix 4, Table 4.18A), indicating a strong enough linear relationship between tensile strength and Brinell hardness.

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Statistical formula (4.36) provides 96.3–99.8% accuracy in calculating tensile strength (Appendix 4, Table 4.18B), which is, practically, as accurate as formula (4.35). The use of these formulas is limited to Brinell hardness range of 150 to 185 HB.

AISI Type 446 (UNS S44600) grade

AISI type 446 is a nonhardening high-chromium grade (nominally 25%, which is the maximum amount compared with other ferritic stainless steels). This grade contains 1.50% manganese and 0.20% carbon, which are also the maximum amounts in ferritic grades. Amounts of silicon, phosphorus, and sulfur are the same as in the majority of ferritic stainless steels. A small addition of nitrogen (0.25% max) is added to increase strength. High-chromium content promotes the best resistance to corrosion and scaling. Applications of AISI type 446 include high-temperature parts for resistance to oxidation, heaters, oil burner parts, and nozzles. The machinability rating of this grade is 55% of that for AISI 1212 free-machining carbon steel (Ref 8, pp.369, 370).

Brinell hardness – tensile strength relationships for AISI type 446 stainless steel are expressed by the following formulas (Appendix 4, Tables 4.19A and 4.19B):

$$\sigma = 395 \times \text{HB} + 16073 \quad (4.37)$$

$$\sigma = 487 \times \text{HB} \quad (4.38)$$

Linear regression formula (4.37) provides 96.6–97.5% accuracy in calculating tensile strength. The correlation coefficient is 0.9110 (Appendix 4, Table 4.19A), indicating a strong enough linear relationship between tensile strength and Brinell hardness.

Statistical formula (4.38) provides 95.0–98.9% accuracy in calculating tensile strength (Appendix 4, Table 4.19B), which is, practically, as accurate as formula (4.37). The use of these formulas is limited to Brinell hardness range of 155–195 HB.

1.4.4. Duplex (ferritic-austenitic) stainless steels

Duplex stainless steels have a mixed structure of body-centered cubic (bcc) ferrite and face-centered cubic (fcc) austenite. The exact amount of each phase is a function of composition and heat treatment. Most grades are designed to contain about equal amounts of each phase in the annealed condition. The principal alloying elements are chromium and nickel, but molybdenum, nitrogen, copper, and tungsten may be added to control structural balance and to impart certain corrosion-resisting characteristics.

The corrosion resistance of duplex stainless steels is like that of austenitic stainless steels with similar alloying contents. However, duplex stainless steels possess higher tensile and yield strengths and better resistance to stress-corrosion cracking than austenitic stainless steels. The toughness of duplex grades is between that of ferritic and austenitic grades (Ref 7, p.842). Currently, there is a standard AISI type 329 grade and eight nonstandard grades of duplex stainless steels (Ref 7, pp.843, 848).

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AISI Type 329 (UNS S32900) grade

AISI type 329 is a two-phase alloy consisting of a ferrite matrix with pools of austenite. This stainless steel contains 25–30% chromium, 3.0–6.0% nickel, 1.0–2.0% molybdenum, 2.0% manganese, and 1.0% silicon. The yield strength of this steel in the annealed condition is more than twice that yield strength of the conventional austenitic stainless steel. For instance, the yield and tensile strengths values of a bar in the annealed condition, made of AISI type 329 duplex stainless steel, are 80,000 psi and 105,000 psi respectively. The yield and tensile strengths of a bar in the annealed condition, made of AISI types 347 or 348 austenitic stainless steels, are 35,000 psi and 90,000 psi respectively (Ref 8, pp.308, 312).

Applications of AISI type 329 include heat exchangers in pulp mills, nitric acid plants, food processing equipment, valves, valve fittings, and pump parts used in extremely corrosive conditions, or where resistance to wear and galling is desired.

Because only a few data points of hardness and tensile strength of AISI type 329 steel were available, the author couldn't perform any kind of analyses. Therefore, the formulas for calculating tensile strength versus Brinell hardness have not been developed.

1.4.5. Precipitation-hardening stainless steels

These stainless steels are chromium-nickel alloys containing precipitation-hardening elements such as copper, aluminum, or titanium. Precipitation-hardening stainless steels can be either austenitic or martensitic in the annealed condition. The austenitic steels in the annealed condition are frequently transformable to martensite through conditioning heat treatments, sometimes with subzero treatment. In most cases, these stainless steels attain high strength by precipitation hardening of the martensitic structure.

Currently, there are four standard and six nonstandard precipitation-hardening stainless steel grades.

The standard grades are: UNS S13800 (PH 13-8 Mo); UNS S15500 (15-5 PH); AISI type 630, or UNS S17400 (17-4 PH); and AISI type 631, or UNS S17700 (17-7 PH).

The nonstandard grades are: UNS S14800 (PH 14-8 Mo); AISI type 632, or UNS S15700 (PH 15-7 Mo); AISI type 633, or UNS S35000 (AM-350); AISI type 634 (UNS S35500 (AM-355); UNS S45000 (Custom 450, XM-25); and UNS S45500 (Custom 455, or XM-16).

The author studied the relationship between the tensile strength (σ) and Brinell hardness (HB) of those grades for which sufficient number of data points were available. The author applied linear regression analysis and statistical treatment of data. As a result of this study, engineering formulas to calculate tensile strength in relationship with Brinell hardness were developed. The formulas, applications, and mechanical properties of these grades are described below.

UNS S13800 (PH 13-8 Mo) grade

UNS S13800 is a martensitic stainless steel containing the following alloying elements: 12.25–13.25% chromium, 7.5–8.5% nickel, 2.0–2.5% molybdenum, and 0.90–1.35% aluminum. The other elements are: manganese (0.10%), silicon (0.10%), nitrogen (0.010%), carbon (0.05%), phosphorus (0.010%), and sulfur (0.008%).

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This steel exhibits high strength and hardness along with good corrosion resistance, ductility, and toughness. Applications of S13800 steel include shafts, valves, fittings, pins, landing gear parts, aircraft components, and nuclear reactor components. The machinability rating of this grade is 35–40% of that for AISI 1212 free-machining carbon steel (Ref 8, p.402).

Brinell hardness – tensile strength relationships for UNS S13800 stainless steel are expressed by the following formulas (Appendix 4, Tables 4.20A and 4.20B):

$$\sigma = 578 \times \text{HB} - 32192 \quad (4.39)$$

$$\sigma = 493 \times \text{HB} \quad (4.40)$$

Linear regression formula (4.39) provides 95.2–99.5% accuracy in calculating tensile strength. The correlation coefficient is 0.9925 (Appendix 4, Table 4.20A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (4.40) provides 94.9–97.1% accuracy in calculating tensile strength (Appendix 4, Table 4.20B), which is less accurate than formula (4.39). The use of these formulas is limited to Brinell hardness range of 270–460 HB.

UNS S15500 (15-5 PH) grade

UNS S15500 is a martensitic stainless steel containing the following alloying elements: 14.0–15.5% chromium, 3.5–5.5% nickel, 2.5–4.5% copper, and 0.15–0.45% niobium and tantalum. The other elements are: manganese (1.0%), silicon (1.0%), carbon (0.07%), phosphorus (0.040%), and sulfur (0.030%).

This steel combines high strength and hardness with excellent corrosion resistance. Applications of S15500 grade include valve parts, fittings and fasteners, shafts, gears, chemical process equipment, paper mill equipment, aircraft components, and nuclear reactor components (Ref 8, p.405).

Brinell hardness – tensile strength relationships for UNS S15500 stainless steel are expressed by the following formulas (Appendix 4, Tables 4.21A and 4.21B):

$$\sigma = 505 \times \text{HB} - 12601 \quad (4.41)$$

$$\sigma = 469 \times \text{HB} \quad (4.42)$$

Linear regression formula (4.41) provides 96.7–99.7% accuracy in calculating tensile strength. The correlation coefficient is 0.9878 (Appendix 4, Table 4.21A), indicating a strong enough linear relationship between tensile strength and Brinell hardness.

Statistical formula (4.42) provides 96.2–99.4% accuracy in calculating tensile strength (Appendix 4, Table 4.21B), which is, practically, as accurate as formula (4.41). The use of these formulas is limited to Brinell hardness range of 275–420 HB.

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AISI Type 630 (UNS S17400) grade

UNS S17400 (also known as 17-4 PH) is a martensitic stainless steel containing the following alloying elements: 15.5–17.5% chromium, 3.0–5.0% nickel, 3.0–5.0% copper, and 0.15–0.45% niobium and tantalum. The other elements are: manganese (1.0%), silicon (1.0%), carbon (0.07%), phosphorus (0.040%), and sulfur (0.030%).

This steel has high resistance to crack propagation. Corrosion resistance and strength are better to that of the regular martensitic chromium-type stainless steel. Applications of S17400 grade include oil field valve parts, chemical process equipment, aircraft fittings, fasteners, pump shafts, nuclear reactor components, gears, paper mill equipment, missile fittings, and jet engine parts (Ref 8, p.375).

Brinell hardness – tensile strength relationships for UNS S17400 stainless steel are expressed by the following formulas (Appendix 4, Tables 4.22A and 4.22B):

$$\sigma = 523 \times \text{HB} - 18525 \quad (4.43)$$

$$\sigma = 469 \times \text{HB} \quad (4.44)$$

Linear regression formula (4.43) provides 97.4–99.9% accuracy in calculating tensile strength. The correlation coefficient is 0.9929 (Appendix 4, Table 4.22A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (4.44) provides 94.7–99.5% accuracy in calculating tensile strength (Appendix 4, Table 4.22B), which is less accurate than formula (4.43). The use of these formulas is limited to Brinell hardness range of 275–420 HB.

AISI Type 631 (UNS S17700) grade

UNS S17700 (also known as 17-7 PH) is an austenitic, chromium-nickel stainless steel containing the following alloying elements: 16.0–18.0% chromium, 6.5–7.75% nickel, and 0.75–1.50% aluminum. The other elements are: manganese (1.0%), silicon (0.04%), carbon (0.09%), phosphorus (0.040%), and sulfur (0.040%).

This steel provides high strength and hardness, excellent fatigue properties, good corrosion resistance, and minimum distortion on heat treatment. Corrosion resistance of this grade in certain conditions of treatment is superior to that of the martensitic chromium stainless steels. Applications of S17700 grade include aircraft structural parts; wire springs, and formed parts.

Brinell hardness – tensile strength relationships for UNS S17700 stainless steel are expressed by the following formulas (Appendix 4, Tables 4.23A and 4.23B):

$$\sigma = 754 \times \text{HB} - 87691 \quad (4.45)$$

$$\sigma = 530 \times \text{HB} \quad (4.46)$$

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Linear regression formula (4.45) provides 97.8–99.8% accuracy in calculating tensile strength. The correlation coefficient is 0.9915 (Appendix 4, Table 4.23A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (4.46) provides 95.2–99.0% accuracy in calculating tensile strength (Appendix 4, Table 4.23B), which is less accurate than formula (4.45). The use of these formulas is limited to Brinell hardness range of 350–435 HB.

UNS S45000 (Custom 450) grade

UNS S45000 is a martensitic stainless steel containing the following alloying elements: 14.0–16.0% chromium, 5.0–7.0% nickel, molybdenum 0.50–1.00%, copper 1.25–1.75%, and niobium 0.40%. The other elements are: manganese (1.0%), silicon (1.0%), carbon (0.05%), phosphorus (0.030%), and sulfur (0.030%).

The main source of technical information on steels (Ref 8) used by the author does not provide examples of applications of S45000 stainless steel.

Brinell hardness – tensile strength relationships for S45000 stainless steel are expressed by the following formulas (Appendix 4, Tables 4.24A and 4.24B):

$$\sigma = 526 \times \text{HB} - 15863 \quad (4.47)$$

$$\sigma = 480 \times \text{HB} \quad (4.48)$$

Linear regression formula (4.47) provides 95.4–99.9% accuracy in calculating tensile strength. The correlation coefficient is 0.9856 (Appendix 4, Table 4.24A), indicating a strong enough linear relationship between tensile strength and Brinell hardness.

Statistical formula (4.48) provides 94.7–99.4% accuracy in calculating tensile strength (Appendix 4, Table 4.24B), which is, practically, as accurate as formula (4.47). The use of these formulas is limited to Brinell hardness range of 255–415 HB.

UNS S45500 (Custom 455) grade

UNS S45500 is a martensitic stainless steel containing the following alloying elements: 11.0–12.5% chromium, 7.5–9.5% nickel, molybdenum 0.50%, niobium 0.10 to 0.50%, copper 1.5–2.5%, and titanium 0.80–1.40%. Also, there are: silicon 0.50%, manganese 0.50%, carbon 0.05%, phosphorus 0.040%, and sulfur 0.030%.

Examples of application of S45500 stainless steel are not provided, by the same reason described earlier.

Brinell hardness – tensile strength relationships for S45500 stainless steel are expressed by the following formulas (Appendix 4, Tables 4.25A and 4.25B):

$$\sigma = 565 \times \text{HB} - 24104 \quad (4.49)$$

$$\sigma = 504 \times \text{HB} \quad (4.50)$$

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Linear regression formula (4.49) provides 95.9–99.4% accuracy in calculating tensile strength. The correlation coefficient is 0.9903 (Appendix 4, Table 4.25A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (4.50) provides 94.5–99.9% accuracy in calculating tensile strength (Appendix 4, Table 4.25B, which is, practically, as accurate as formula (4.49). The use of these formulas is limited to Brinell hardness range of 290–470 HB.

Concluding Remarks on Stainless Steels

1. Stainless steels are designated according to the AISI / UNS identification number and divided into five categories: austenitic, martensitic, ferritic, duplex (ferritic-austenitic), and precipitation-hardening stainless steels.

2. Currently, there are 56 standard grades of stainless steels, including:

- 29 grades of austenitic steel
- 12 grades of martensitic steel
- 10 grades of ferritic steel
- 1 grade of duplex (ferritic-austenitic) steel
- 4 grades of precipitation-hardening steel

3. Machinability ratings of stainless steels vary from 40% (AISI types 440B and 440C martensitic grades; UNS S13800 precipitation-hardening grade) to 90% (AISI 416 and 416Se martensitic grades). The majority of grades of all five categories exhibit the machinability ratings from 45 to 55% of that for AISI 1212 free-machining carbon steel.

4. Study of the tensile strength – Brinell hardness relationships conducted by the author, resulted in developing 25 statistical and 25 linear regression formulas. These formulas are summarized in Table 1.4.

5. Strength-to-hardness ratios for austenitic stainless steels are the highest and range from 499 (AISI type 308) to 557 (AISI types 302 and 302B).

Strength-to-hardness ratios for martensitic stainless steels range from 492 (AISI types 416 and 416Se) to 499 (AISI types 414, 440A, and 440B).

Strength-to-hardness ratios for ferritic stainless steels are the lowest and range from 461 (AISI type 405) to 487 (AISI type 446).

Strength-to-hardness ratios for precipitation-hardening stainless steels range from 469 (UNS types S15500 and S17400) to 530 (AISI type 631; UNS S17700).

6. High accuracy of statistical formulas for calculating tensile strength is obtained through multiplication Brinell hardness number by appropriate strength-to-hardness ratio.

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7. The correlation coefficients range from 0.9030–0.9999, indicating that linear regression formulas provide high accuracy in calculating tensile strength versus Brinell hardness.

8. The applications of statistical and linear regression formulas are limited to Brinell hardness ranges shown in this Table 1.4.

Table 1.4. Formulas for calculating tensile strength versus Brinell hardness

Category of Stainless Steel	AISI (UNS) Grades	Brinell hardness range, HB	Statistical Formula	Linear Regression Formula	Correlation Coefficient
Austenitic steel	201 (S20100)	250–405	$\sigma = 512 \times \text{HB}$	$\sigma = 606 \times \text{HB} - 31737$	0.9637
Austenitic steel	301 (S30100)	250–405	$\sigma = 525 \times \text{HB}$	$\sigma = 609 \times \text{HB} - 27508$	0.9756
Austenitic steel	302, 302B	145–255	$\sigma = 557 \times \text{HB}$	$\sigma = 353 \times \text{HB} + 35507$	0.9873
Austenitic steel	304, 304N, 304HN	145–310	$\sigma = 502 \times \text{HB}$	$\sigma = 325 \times \text{HB} + 35246$	0.9842
Austenitic steel	308 (S30800)	240–405	$\sigma = 499 \times \text{HB}$	$\sigma = 695 \times \text{HB} - 61198$	0.9920
Austenitic steel	316, 316L, 316F, 316N	140–190	$\sigma = 536 \times \text{HB}$	$\sigma = 231 \times \text{HB} + 47879$	0.9030
Austenitic steel	321 (S32100)	150–185	$\sigma = 534 \times \text{HB}$	$\sigma = 339 \times \text{HB} + 32879$	0.9564
Austenitic steel	347, 348	160–215	$\sigma = 517 \times \text{HB}$	$\sigma = 156 \times \text{HB} + 67234$	0.9213
Martensitic steel	403 (S40300)	145–225	$\sigma = 492 \times \text{HB}$	$\sigma = 536 \times \text{HB} - 7792$	0.9994
Martensitic steel	414 (S41400)	225–430	$\sigma = 499 \times \text{HB}$	$\sigma = 513 \times \text{HB} - 4350$	0.9952
Martensitic steel	416, 416Se	150–370	$\sigma = 492 \times \text{HB}$	$\sigma = 527 \times \text{HB} - 9448$	0.9936
Martensitic steel	420 (S42000)	190–600	$\sigma = 494 \times \text{HB}$	$\sigma = 498 \times \text{HB} - 1193$	0.9999
Martensitic steel	431 (S43100)	260–425	$\sigma = 498 \times \text{HB}$	$\sigma = 553 \times \text{HB} - 18263$	0.9939
Martensitic steel	440A (S44002)	205–510	$\sigma = 499 \times \text{HB}$	$\sigma = 524 \times \text{HB} - 7353$	0.9996
Martensitic steel	440B (S44003)	210–555	$\sigma = 499 \times \text{HB}$	$\sigma = 511 \times \text{HB} - 3677$	0.9999

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Table 1.4 continued

Martensitic steel	440C (S44004)	220–580	$\sigma = 493 \times \text{HB}$	$\sigma = 488 \times \text{HB} + 1674$	0.9995
Ferritic steel	405 (S40500)	130–185	$\sigma = 461 \times \text{HB}$	$\sigma = 410 \times \text{HB} + 7905$	0.9467
Ferritic steel	430, 434, 435, 436	150–185	$\sigma = 466 \times \text{HB}$	$\sigma = 431 \times \text{HB} + 5810$	0.9708
Ferritic steel	446 (S44600)	155–195	$\sigma = 487 \times \text{HB}$	$\sigma = 395 \times \text{HB} + 16073$	0.9110
Precipitation hardening steel	(S13800)	270–460	$\sigma = 493 \times \text{HB}$	$\sigma = 578 \times \text{HB} - 32192$	0.9925
Precipitation hardening steel	(S15500)	275–420	$\sigma = 469 \times \text{HB}$	$\sigma = 505 \times \text{HB} - 12601$	0.9878
Precipitation hardening steel	630 (S17400)	275–420	$\sigma = 469 \times \text{HB}$	$\sigma = 523 \times \text{HB} - 18525$	0.9929
Precipitation hardening steel	631 (S17700)	350–435	$\sigma = 530 \times \text{HB}$	$\sigma = 754 \times \text{HB} - 87691$	0.9915
Precipitation hardening steel	(S45000)	255–415	$\sigma = 480 \times \text{HB}$	$\sigma = 526 \times \text{HB} - 15863$	0.9856
Precipitation hardening steel	(S45500)	290–470	$\sigma = 504 \times \text{HB}$	$\sigma = 565 \times \text{HB} - 24104$	0.9903

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1.5. Tool Steels

Tool steels are carbon, alloy, or high-speed steels, capable of being hardened and tempered. They are used to make tools for cutting, forming, and shaping of work materials. Tool steels are also used as the work materials where resistance to wear, strength, toughness, and other properties are selected for optimum performance.

According to the American Iron and Steel Institute (AISI) classification, tool steels are divided into seven major groups, each group identified by letter-numeric symbols. Within the various groups there are subdivisions (Ref 8, p.431, Ref 14, p.6):

1. Water-hardening tool steels, W
2. Shock-resisting tool steels, S
3. Cold-work tool steels:
 - Oil-hardening types, O
 - Air-hardening, medium alloy types, A
 - High-carbon, high-chromium types, D
4. Mold steels, P
5. Low alloy special-purpose tool steels, L
6. Hot-work tool steels:
 - Chromium-base types, H10–H19
 - Tungsten-base types, H21–H26
 - Molybdenum-base types, H41–H43
7. High-speed tool steels:
 - Tungsten-base types, T
 - Molybdenum-base types, M

The UNS designation of tool steels consists of the letter T (assigned to tool steel), followed by five digits. Water-hardening types are T723xx; shock-resisting types are T419xx; oil-hardening types are T315xx; air-hardening types are T301xx; high-chromium types are T304xx; low-alloy, special purpose types are T612xx; mold steels are T516xx; hot work types are T208xx; high-speed, tungsten-base types are T120xx; and high-speed, molybdenum-base types are T113xx.

The author studied the relationship between the tensile strength (σ) and Brinell hardness (HB) of those tool steel grades, for which a sufficient number of data points were available, so the linear regression analysis and statistical treatment of data have been performed. As a result of this study, engineering formulas for calculating tensile strength versus Brinell hardness were developed. Applications and mechanical properties of tool steels are described below.

1.5.1. Water-hardening tool steels

The water-hardening tool steels (W steels in the AISI classification system) are essentially carbon steels with small amounts of principal alloying elements (chromium, nickel, vanadium,

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tungsten, and molybdenum) and small amounts of secondary alloying elements (manganese and silicon). As a result of such chemical compositions, the water-hardening tool steels are the least expensive of tool steels.

In comparison with other tool steels, the water-hardening tool steels have shallow depth of hardening, good toughness, poor resistance to the softening effect of heat, fair-to-good wear resistance, and the best machinability. The water-hardening tool steels have a machinability rating of 100%, as a basis for comparison with other groups of tool steels. When compared with free-machining AISI 1212 steel, the machinability rating of water-hardening steels is 40% (Ref 8, p.432).

Originally, water-hardening tool steels included six grades (Ref 15, p.297): W1 and W2 produced to a range of 0.60–1.40 % carbon; W3, W4, W5, and W7 produced to 1.00% carbon. All grades contained 0.25% manganese and 0.25% silicon). W4, W5, and W7 grades contained various amounts of chromium (from 0.10 to 0.50%). W2, W3, and W7 grades contained various amounts of vanadium (from 0.10 to 0.50%).

Currently, there are three standard grades: **W1 (UNS T72301)**, **W2 (UNS T72302)**, and **W5 (UNS T72305)** of water-hardening steels. They are produced to the same amount of nickel (0.20%), molybdenum (0.10%), tungsten (0.15%), and copper (0.20%).

These standard grades have the same amount of manganese (0.10–0.40)% and silicon (0.10–0.40)%, but different amounts of chromium (0.15% in W1 and W2 grades; 0.40–0.60% in W5 grade) and vanadium (0.10% in W1 and W5 grades, and 0.15–0.35% in W2 grade). They are produced to various carbon ranges (Ref 8, p.432): 0.60–1.40% (W1 and W2 grades), and 1.05–1.15% (W5).

Applications of these standard grades include shear blades, blanking dies, reamers, threading dies, taps, twist drills, lathe tools, coining dies, woodworking tools, and cutlery (Ref 14, p.125).

Information on mechanical properties was available only for **AISI type W1 steel** in the form of graphs showing relationships between strengths (tensile and yield) versus Rockwell-C hardness ranging from 20 to 56 HRC (Ref 8, p.436).

The author converted given HRC hardness numbers into Brinell hardness numbers using equations 1.12–1.19 described earlier (Section 1.1.2, pp.5-7). Tensile strength – Brinell hardness relationships are expressed by the following formulas (Appendix 5, Tables 5.1A and 5.1B):

$$\sigma = 379 \times \text{HB} + 47330 \quad (5.1)$$

$$\sigma = 523 \times \text{HB} \quad (5.2)$$

Linear regression formula (5.1) provides 90.7–99.7% accuracy in calculating tensile strength. The correlation coefficient is 0.9615 (Appendix 5, Table 5.1A), indicating a strong enough linear relationship between tensile strength and Brinell hardness.

Statistical formula (5.2) provides 87.3–99.2% accuracy in calculating tensile strength (Appendix 5, Table 5.1B), which is less accurate than formula (5.1). The use of these formulas is limited to Brinell hardness range of 225–460 HB.

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1.5.2. Shock-resisting tool steels

The shock-resisting tool steels (S steels in the AISI classification system) have been developed to produce good combinations of high hardness, high strength, and high toughness or impact fracture resistance. Besides manganese, chromium, and molybdenum, which are typical alloying elements for hardenability of tool steels, silicon is a major alloying element, which provides tempering resistance and produces a microstructure with reduced sensitivity to fracture.

Shock-resisting steels were originally developed for springs and are still widely used for spring applications where good fatigue resistance is required (Ref 14, p.165).

Currently, there are six standard grades of shock-resisting steels: AISI types S1, S2, S4, S5, S6, and S7. They contain various amounts of alloying elements, but about the same amounts of carbon (0.40–0.65%) and the same amounts of phosphorus (0.03%) and sulfur (0.03%). Machinability rating of these steels is about 75% of that for water-hardening tool steels (Ref 8, p.436). Because group S steels exhibit excellent toughness at high strength levels, they are often considered for nontooling applications (Ref 7, p.767).

AISI Type S1 (UNS T41901) steel

AISI type S1 is chromium-tungsten tool steel containing 1.00–1.80% chromium, 1.50–3.00% tungsten, 0.15–0.30% vanadium, 0.50% molybdenum, 0.15–1.20% silicon, and 0.10–0.40% manganese.

The S1 steel is also referred to as tungsten chisel steel because of its wide use in shock-resisting tools, such as chisels, beading tools, shear blades; forging, forming, and striking dies; rivet busters, punches, bolt clippers, and heading dies for square-headed bolts (Ref 15, p.424). Compared to the other S-type steels, S1 has slightly better impact toughness and wear resistance, primarily because of its tungsten content. The deep hardening of S1 steel is due to chromium, silicon, manganese, or molybdenum additions.

Brinell hardness – tensile strength relationships for S1 tool steel are expressed by the following formulas (Appendix 5, Tables 5.2A and 5.2B):

$$\sigma = 543 \times \text{HB} - 11459 \quad (5.3)$$

$$\sigma = 517 \times \text{HB} \quad (5.4)$$

Linear regression formula (5.3) provides 94.6–97.5% accuracy in calculating tensile strength. The correlation coefficient is 0.9890 (Appendix 5, Table 5.2A), indicating a strong enough linear relationship between tensile strength and Brinell hardness.

Statistical formula (5.4) provides 90.4–97.0% accuracy in calculating tensile strength (Appendix 5, Table 5.2B), which is less accurate than formula (5.3). The use of these formulas is limited to Brinell hardness range of 210–605 HB.

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AISI Type S2 (UNS T41902) steel

AISI type S2 steel is produced to a range of 0.90–1.20% silicon, 0.30–0.60% molybdenum, and 0.30–0.50% manganese. This steel doesn't have chromium, but contains 0.50% vanadium, which is more than that in any grade of S-type steels.

Type S2 is an extremely tough, strong steel that is recommended for applications where toughness is required above all other qualities. It has a hard case and tough core after heat treatment (Ref 8, p.436). This steel is used for chisels (hand and pneumatic), punches, various types of dies (trimming, crimping, swaging, and coining), shear blades, wrenches, and jaws (Ref 15, p.410).

The hardness – tensile strength relationship for S2 tool steel was derived from the graph (Ref 8, p.439), which was analyzed similar to that for W1 tool steel. As a result of this analysis, the following formulas were developed (Appendix 5, Tables 5.3A and 5.3B):

$$\sigma = 631 \times \text{HB} - 50131 \quad (5.5)$$

$$\sigma = 494 \times \text{HB} \quad (5.6)$$

Linear regression formula (5.5) provides 89.6–98.7% accuracy in calculating tensile strength. The correlation coefficient is 0.9929 (Appendix 5, Table 5.3A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (5.6) provides 90.1–99.8% accuracy in calculating tensile strength (Appendix 5, Table 5.3B), which is slightly more accurate than formula (5.5). The use of these formulas is limited to Brinell hardness range of 225–560 HB.

AISI Type S4 (UNS T41904) steel

AISI type S4 is silicon-manganese steel produced to a range of 1.75–2.25% silicon, and 0.60–0.95% manganese. This steel contains 0.35% chromium and 0.35% vanadium, but doesn't have molybdenum. Type S4 is tough steel with good resistance to battering and shock at relatively high hardness (Ref 8, p.436). Applications of this steel are similar to those described for type S2 steel.

AISI Type S5 (UNS T41905) steel

AISI type S5 is silicon-manganese steel produced to a range of 1.75–2.25% silicon, 0.60–1.00% manganese, and 0.20–1.35% molybdenum. This steel contains 0.50% chromium and 0.35% vanadium.

Type S5 is an extremely tough tool steel with outstanding shock and abrasion resistance. Besides its use for various battering and shock-resisting tools, this steel can also be used for non-tooling applications.

Brinell hardness – tensile strength relationships for S5 tool steel are expressed by the following formulas (Appendix 5, Tables 5.4A and 5.4B):

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$$\sigma = 561 \times \text{HB} - 19646 \quad (5.7)$$

$$\sigma = 521 \times \text{HB} \quad (5.8)$$

Linear regression formula (5.7) provides 93.2–99.9% accuracy in calculating tensile strength. The correlation coefficient is 0.9951 (Appendix 5, Table 5.4A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (5.8) provides 92.6–98.4% accuracy in calculating tensile strength (Appendix 5, Table 5.4B), which is slightly less accurate than formula (5.7). The use of these formulas is limited to Brinell hardness range of 210–635 HB.

AISI Type S7 (UNS T41907) steel

AISI type S7 is chromium-molybdenum air-hardening steel produced to a range of 3.00–3.50% chromium, 1.30–1.80% molybdenum, and 0.20–1.00% silicon. This steel contains 0.20–0.30% vanadium and 0.20–0.80% manganese. Type S7 is an air-hardening steel with high impact and shock resistance and excellent toughness.

Applications of S7 and S1 grades are similar. Both grades are also used for hot punching and shearing, which require some heat resistance (Ref 7, p.766).

Brinell hardness – tensile strength relationships for S7 tool steel are expressed by the following formulas (Appendix 5, Tables 5.5A and 5.5B):

$$\sigma = 553 \times \text{HB} - 19876 \quad (5.9)$$

$$\sigma = 510 \times \text{HB} \quad (5.10)$$

Linear regression formula (5.9) provides 96.4–99.8% accuracy in calculating tensile strength. The correlation coefficient is 0.9978 (Appendix 5, Table 5.5A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (5.10) provides 87.3–99.8% accuracy in calculating tensile strength (Appendix 5, Table 5.5B), which is less accurate than formula (5.9). The use of these formulas is limited to Brinell hardness range of 205–615 HB.

1.5.3. Cold work tool steels

Cold work tool steels do not have the alloy content necessary to be resistant to softening at elevated temperature. They are restricted in applications that require prolonged or repeated heating above 400–500 °F (205–260 °C). Within the cold work tool steels category there are three groups: oil-hardening steels, or group **O**; air-hardening steels, or group **A**; and high-carbon, high-chromium steels, or group **D** (Ref 7, p.763).

Oil-hardening tool steels

The oil-hardening tool steels, designated as group **O**, derive their high hardness and wear

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resistance from high carbon and moderate alloy contents. Currently, there are four standard grades in this category: O1, O2, O6, and O7. All grades are produced to various amounts of carbon and alloying elements, but to the same limited contents of phosphorus and sulfur (0.030% max).

AISI Type O1 (UNS T31501) steel

AISI type O1 is general-purpose tool steel produced to the same amounts of chromium and tungsten (0.40–0.60%) and to the following amounts of other alloying elements: 0.30% vanadium, 0.50% silicon, and 1.00–1.40% manganese. Carbon content is 0.85–1.00%. This grade is resistant to abrasion, has sufficient toughness, and exhibits extreme dimensional accuracy.

Applications of type O1 steel include blanking, forming, drawing, molding, and trimming dies; spindles, thread gages, collets, and stamps. The machinability rating of this grade is between 65 and 75% of that for water-hardening tool steels (Ref 8, p.440).

Brinell hardness – tensile strength relationships for O1 tool steel are expressed by the following formulas (Appendix 5, Tables 5.6A and 5.6B):

$$\sigma = 546 \times \text{HB} - 26657 \quad (5.11)$$

$$\sigma = 474 \times \text{HB} \quad (5.12)$$

Linear regression formula (5.11) provides 91.7–99.4% accuracy in calculating tensile strength. The correlation coefficient is 0.9806 (Appendix 5, Table 5.6A), indicating a strong enough linear relationship between tensile strength and Brinell hardness.

Statistical formula (5.12) provides 91.7–99.7% accuracy in calculating tensile strength (Appendix 5, Table 5.6B), which is as accurate as formula (5.11). The use of these formulas is limited to Brinell hardness range of 235–480 HB.

AISI Type O2 (UNS T31502) steel

AISI type O2 steel contains 0.30% molybdenum and vanadium, 0.35% chromium, 0.50% silicon, 1.40–1.80% manganese, and 0.85–0.95% carbon.

This grade shows very little size change or warpage during the hardening operation, less than that for type O1. Applications of O2 steel are similar to O1 steel. The machinability rating of O2 grade is between 90 and 100% of that for water-hardening tool steels (Ref 8, p.440).

Hardness – tensile strength relationship for O2 tool steel was derived from the graph (Ref 8, p.444), which was analyzed similar to that for W1 tool steel. As a result of this analysis, the following formulas were developed (Appendix 5, Tables 5.7A and 5.7B):

$$\sigma = 545 \times \text{HB} - 15192 \quad (5.13)$$

$$\sigma = 503 \times \text{HB} \quad (5.14)$$

Linear regression formula (5.13) provides 97.7–99.6% accuracy in calculating tensile

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strength. The correlation coefficient is 0.9987 (Appendix 5, Table 5.7A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (5.14) provides 92.8–99.5% accuracy in calculating tensile strength (Appendix 5, Table 5.7B), which is less accurate than formula (5.13). The use of these formulas is limited to Brinell hardness range of 225–540 HB.

AISI Type O6 (UNS T31506) steel

AISI type O6 steel is produced to a range of 0.55–1.50% silicon, 0.30–1.10% manganese, 0.20–0.30% molybdenum, 0.30% chromium, and 1.25–1.55% carbon. In the annealed condition, about one third of the carbon is present as graphitic carbon (free graphite in the microstructure), which improves machinability. The machinability rating of O6 grade is 125% in comparison with 100% of that for water-hardening tool steels (Ref 8, p.441).

AISI Type O7 (UNS T31507) steel

AISI type O7 steel is produced to a range of 1.00–2.00% tungsten, 0.35–0.85% chromium, 0.30% molybdenum, 0.40% vanadium, 0.60% silicon, 1.00% manganese, and 1.10–1.30% carbon. Tungsten promotes harder carbides and a higher carbon content. Type O7 grade maintains a keen cutting edge. Applications of this steel include punches, dies, and knives where a keen cutting edge is required. The machinability rating of O7 steel in the annealed condition is 85% of that for water-hardening tool steel (Ref 8, p.441).

Brinell hardness – tensile strength relationships for O7 tool steel are expressed by the following formulas (Appendix 5, Tables 5.8A and 5.8B):

$$\sigma = 593 \times \text{HB} - 51470 \quad (5.15)$$

$$\sigma = 477 \times \text{HB} \quad (5.16)$$

Linear regression formula (5.15) provides 94.9–99.9% accuracy in calculating tensile strength. The correlation coefficient is 0.9959 (Appendix 5, Table 5.8A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (5.16) provides 90.5–99.4% accuracy in calculating tensile strength (Appendix 5, Table 5.8B), which is less accurate than formula (5.15). The use of these formulas is limited to Brinell hardness range of 290–550 HB.

Air-hardening tool steels

The air-hardening tool steels, designated as group A, achieve their processing and performance characteristics from high carbon and moderately-high alloy contents. Currently, there are eight standard grades in this category: A2, A3, A4, A6, A7, A8, A9, and A10. All grades have high hardenability and a high degree of dimensional stability in heat treatment. This group of steels exhibits good wear resistance, fatigue life, toughness, and deep-hardening qualities (Ref 8, p.445). Air-hardening steels are produced to various amounts of carbon and alloying elements, but to the

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same limited contents of phosphorus and sulfur (0.030% max).

Most of the group A steels fall into two subgroups: (a) *chromium* air-hardening grades containing 4.75–5.75% chromium and up to 1.0% *manganese* (A2, A3, A7, A8, and A9) and (b) *manganese* air-hardening grades containing 1.8–3.2% manganese and 0.90–2.20% chromium (A4, A5, and A6). Chromium air-hardening types are more readily available and by far the more widely used. The chromium types have higher wear resistance (at equivalent carbon contents) and greater hot hardness than manganese air-hardening types (Ref 15, p.509). A9 chromium air-hardening grade is the toughest steel in this subgroup, but also the least wear resistant. The manganese types, however, are less wear resistant and more difficult to machine (Ref 15, p.525).

Applications of air-hardening tool steels include cold forming, blanking and bending dies, forming rolls, drill bushings, knurling tools, muster dies and gages, and other uses where low distortion in heat treatment and good wear resistance are required. The machinability rating of these steels is about 65% of that for the water-hardening tool steels (Ref 8, p.445).

Data showing the relationship between tensile properties and hardness were available in the form of graphs, but only for A2 and A6 air-hardening steels (Ref 8, p.447). The author analyzed these graphs and developed formulas for calculating tensile strength versus Brinell hardness. Hardness conversion equations (Section 1.1.2. Rockwell hardness, pp.11) were used to obtain Brinell hardness numbers.

AISI Type A2 (UNS T30102) steel

AISI type A2 steel is produced to a range of 4.75–5.50% chromium, 0.90–1.40% molybdenum, and 0.15–0.50% vanadium. This steel also contains 0.50% silicon, 1.00% manganese, and 0.95–1.05% carbon.

Brinell hardness – tensile strength relationships for A2 tool steel are expressed by the following formulas (Appendix 5, Tables 5.9A and 5.9B):

$$\sigma = 552 \times \text{HB} - 25062 \quad (5.17)$$

$$\sigma = 485 \times \text{HB} \quad (5.18)$$

Linear regression formula (5.17) provides 95.2–99.7% accuracy in calculating tensile strength. The correlation coefficient is 0.9986 (Appendix 5, Table 5.9A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (5.18) provides 91.7–99.2% accuracy in calculating tensile strength (Appendix 5, Table 5.9B), which is less accurate than formula (5.17). The use of these formulas is limited to Brinell hardness range of 225–520 HB.

AISI Type A6 (UNS T30106) steel

AISI type A6 steel is produced to a range of 0.90–1.20% chromium, 0.90–1.20% molybdenum, 1.80–2.50% manganese, 0.50% silicon, and 0.65–0.75% carbon.

Brinell hardness – tensile strength relationships for A6 tool steel are expressed by the follow-

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ing formulas (Appendix 5, Tables 5.10A and 5.10B):

$$\sigma = 572 \times \text{HB} - 3689 \quad (5.19)$$

$$\sigma = 565 \times \text{HB} \quad (5.20)$$

Linear regression formula (5.19) provides 96.4–99.2% accuracy in calculating tensile strength. The correlation coefficient is 0.9720 (Appendix 5, Table 5.10A), indicating a strong enough linear relationship between tensile strength and Brinell hardness.

Statistical formula (5.20) provides 96.3–99.3% accuracy in calculating tensile strength (Appendix 5, Table 5.9B), which is as accurate as formula (5.19). The use of these formulas is limited to Brinell hardness range of 480–615 HB.

High-carbon, high-chromium tool steels

The high-carbon, high-chromium tool steels, designated as group D, are the most highly alloyed cold-work steels. Currently, there are five standard grades: D2, D3, D4, D5, and D7. They are all characterized by high carbon content, from 1.40 to 2.6%, and chromium, as the major alloying element, from 11.0 to 13.5%.

All grades (except D3) containing molybdenum (0.70–1.20%) are air hardening and, therefore, exhibit a high degree of dimensional stability in heat treatment. D7 steel is produced to a range of 3.80–4.40% vanadium; the other four grades contain nominally 1.00% vanadium. Only D3 steel contains tungsten (1.0% max). Cobalt is added to D2 steel in the amount of 1.0% and to D5 steel in the amount of 2.50–3.50% (Ref 8, p.449).

All five standard types of these steels contain equal amounts of the following elements: manganese (0.60% max), silicon (0.60% max), and nickel (0.30% max); sulfur and phosphorus are present in the amount of 0.030% max (Ref 14, p. 203).

Applications of high-carbon, high-chromium steels include spindles, hobs, cold rolls, slitting cutters, blanking dies, forming dies, coining dies, bushings, taps, broaches, sand blast nozzles, plug and ring gages (Ref 8, p.449).

The author did not develop formulas for tensile strength – Brinell hardness relation because the data of such mechanical properties were not available.

1.5.4. Mold steels

The mold steels, designated as group P, are used for plastic molding and some die casting applications. Currently, there are seven standard grades: P2, P3, P4, P5, P6, P20, and P21. Grades P2 to P6 are very low in carbon content (0.05–0.25%), and are usually supplied at very low hardness to facilitate cold hubbing* of the impression. They are then carburized to develop the required surface properties for injection and compression molds for plastics. Grades P20 (0.28–0.40% carbon) and P21 (0.18–0.22% carbon) are usually supplied in the prehardened condition, so the cavity can be machined, and the mold placed directly in service. The machinability rating of P2, P3, and P4 steels is 80–90% of that for the water-hardening tool steels. Other machinability ratings are: 60% for steel P5, and 65% for steel P21 (Ref 8, p.453).

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The tensile strength data and the corresponding Rockwell C hardness numbers were available only for AISI types P6 and P20 mold steels. Therefore, mechanical properties and statistical analysis are provided for these two grades.

AISI Type P6 (UNS T51606) steel

AISI type P6 steel is produced to a range of 1.25–1.75% chromium, 3.25–3.75% nickel, 0.20–0.60% manganese, 0.40% silicon, and 0.05–0.15% carbon. The machinability rating is 40% of that for the water-hardening tool steels (Ref 8, p.453).

Tensile strength data and HRC hardness numbers for AISI type P6 steel provided by the graph (Ref 8, p.456), were used to develop formulas expressing Brinell hardness – tensile strength relationships (Appendix 5, Tables 5.11A and 5.11B):

$$\sigma = 510 \times \text{HB} - 6106 \quad (5.21)$$

$$\sigma = 489 \times \text{HB} \quad (5.22)$$

Linear regression formula (5.21) provides 97.6–99.9% accuracy in calculating tensile strength. The correlation coefficient is 0.9980 (Appendix 5, Table 5.11A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (5.22) provides 97.8–99.9% accuracy in calculating tensile strength (Appendix 5, Table 5.11B), which is as accurate as formula (5.21). The use of these formulas is limited to Brinell hardness range of 225–375 HB.

AISI Type P20 (UNS T51620) steel

AISI type P20 steel is produced to a range of 1.40–2.00% chromium, 0.30–0.65% molybdenum, 0.60–1.00% manganese, 0.20–0.80% silicon, and 0.28–0.40% carbon. Approximate machinability rating is 65% of that for the water-hardening tool steels (Ref 8, p.453).

Tensile strength data and HRC hardness numbers for P20 steel given in the table (Ref 8, p.454), were used to develop formulas expressing Brinell hardness – tensile strength relationships (Appendix 5, Tables 5.12A and 5.12B):

$$\sigma = 543 \times \text{HB} - 11173 \quad (5.23)$$

$$\sigma = 516 \times \text{HB} \quad (5.24)$$

Linear regression formula (5.23) provides 97.6–99.9% accuracy in calculating tensile strength. The correlation coefficient is 0.9980 (Appendix 5, Table 5.12A), indicating a strong linear relationship between tensile strength and Brinell hardness.

*Hubbing is a technique for forming mold cavities by forcing hardened steel master hubs, which replicate the cavities to be formed into softer die blanks (Ref. 14, p.291).

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Statistical formula (5.24) provides 97.2–99.6% accuracy in calculating tensile strength (Appendix 5, Table 5.12B), which is as accurate as formula (5.23). The use of these formulas is limited to Brinell hardness range of 255–545 HB.

1.5.5. Low-alloy special-purpose tool steels

The low-alloy special-purpose tool steels, or group **L**, contain small amounts of chromium, vanadium, nickel, and molybdenum. In the past, there were five L-grades (L1, L3, L4, L5, L7) and three F-grades (F1, F2, F3) in this group, but because of falling demand, only grades L2 and L6 remain (Ref 7, pp.762, 767).

Applications for the L steels include tools such as precision gages, cold-heading dies, swaging dies, shears, punches, and drills (Ref 14, p.141). Group L steels are also used for machine parts such as arbors, cams, chucks, and collets (Ref 7, p.767).

AISI Type L2 (UNS T61202) steel

L2 steel is manufactured with various carbon levels: 0.45–0.65% (L2, medium-carbon grade) and 0.65–1.10% (L2, high-carbon grade). Principal alloying elements are chromium (0.70–1.20%) and vanadium (0.10–0.30%). The other elements are molybdenum (0.25% max), manganese (0.10–0.90%), and silicon (0.50% max).

Tensile strength data and the Rockwell hardness numbers for L2 steel given in the table (Ref 7, p.767), were used to develop formulas expressing Brinell hardness – tensile strength relationships (Appendix 5, Tables 5.13A and 5.13B):

$$\sigma = 560 \times \text{HB} - 22467 \quad (5.25)$$

$$\sigma = 503 \times \text{HB} \quad (5.26)$$

Linear regression formula (5.25) provides 94.5–99.7% accuracy in calculating tensile strength. The correlation coefficient is 0.9971 (Appendix 5, Table 5.13A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (5.26) provides 94.4–99.0% accuracy in calculating tensile strength (Appendix 5, Table 5.13B), which is as accurate as formula (5.25). The use of these formulas is limited to Brinell hardness range of 210–545 HB.

AISI Type L6 (UNS T61206) steel

L6 steel is produced to a range of 0.65–0.75% carbon. Principal alloying elements are chromium (0.60–1.20%) and nickel (1.25–2.00%). The other elements are vanadium (0.20–0.30%), molybdenum (0.50% max), manganese (0.25–0.80%), and silicon (0.50% according to Ref 7, p.759; or 0.25% according to Ref 14, p.141).

Tensile strength data and the Rockwell hardness numbers for L6 steel given in the table (Ref 7, p.767), were used to develop formulas expressing Brinell hardness – tensile strength relationships (Appendix 5, Tables 5.14A and 5.14B):

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$$\sigma = 579 \times \text{HB} - 26083 \quad (5.27)$$

$$\sigma = 509 \times \text{HB} \quad (5.28)$$

Linear regression formula (5.27) provides 93.2–99.6% accuracy in calculating tensile strength. The correlation coefficient is 0.9959 (Appendix 5, Table 5.14A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (5.28) provides 91.1–98.0% accuracy in calculating tensile strength (Appendix 5, Table 5.14B), which is less accurate than formula (5.27). The use of these formulas is limited to Brinell hardness range of 195–545 HB.

1.5.6. Hot-work tool steels

Many manufacturing operations involve punching, shearing, or forming of metals at high temperatures. Hot-work steels (group **H**) have been developed to withstand the combinations of heat, pressure, and abrasion associated with operations (Ref 7, p.762).

The hot-work tool steels are subdivided into three classes: chromium, tungsten, and molybdenum.

Chromium-type steels

The chromium hot-work steels contain chromium (nominally 5%) as a major alloying element. Currently, there are six standard grades: H10, H11, H12, H13, H14, and H19. All of them are characterized as medium-carbon grades (0.30–0.45% carbon) and contain 0.30% (maximum) nickel.

The grades containing molybdenum, H10, H11, H12, and H13, are the most widely used of all the hot-work steels, and characterized by high hardenability and excellent toughness. The chromium-tungsten H14 grade and the chromium-tungsten-cobalt H19 grade offer greater resistance to softening, but they are less ductile.

The machinability ratings are: 55–65% for types H11 and H12, 45–55% for type H13, and 60–70% for type H19. These ratings are based on the water-hardening tool steels with a machinability rating of 100% (Ref 8, p.457).

Typical applications of chromium hot-work steels include dies for aluminum, zinc, and magnesium castings; forging dies; punches, piercers, mandrels, hot-extrusion tooling, shear blades, and all types of dies for hot work (Ref 14, p.222).

Information on mechanical properties was found only for H11, H12, and H13 grades in the form of graphs showing relationships between strengths (tensile and yield) versus HRC hardness (Ref 8, p.461).

AISI Types H11 (UNS T20811) and H13 (UNS T20813) steels

Both grades are produced to the same amount of chromium (4.75–5.50%), silicon (0.80–1.20%), and manganese (0.20–0.50%), but contain various amounts of other elements: molybdenum (1.10–1.60% in H11), (1.10–1.75% in H13), and vanadium (0.30–0.60% in H11),

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(0.80–1.20% in H13), as shown in (Ref 14, p.219).

In addition to the above-mentioned typical applications of chromium hot-work steels, grade H11 is used to make certain highly-stressed structural parts, particularly in aerospace technology (Ref 7, p.762), and grade H13 has been used for special modular quick-change tooling parts.

Tensile strength data and HRC hardness numbers for AISI types H11 and H13 steels provided by the graph (Ref 8, p.461), were used to develop formulas expressing Brinell hardness – tensile strength relationships (Appendix 5, Tables 5.15A and 5.15B):

$$\sigma = 555 \times \text{HB} - 19290 \quad (5.29)$$

$$\sigma = 502 \times \text{HB} \quad (5.30)$$

Linear regression formula (5.29) provides 96.5–100% accuracy in calculating tensile strength. The correlation coefficient is 0.9990 (Appendix 5, Table 5.15A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (5.30) provides 95.6–99.4% accuracy in calculating tensile strength (Appendix 5, Table 5.15B), which is slightly less accurate than formula (5.29). The use of these formulas is limited to Brinell hardness range of 225–560 HB.

AISI Type H12 (UNS T20812) steel

H12 steel is produced to a range of 4.75–5.50% chromium, 1.25–1.75% molybdenum, 1.00–1.70% tungsten, 0.50% vanadium, 0.20–0.50% manganese, 0.80–1.20% silicon, and 0.30–0.40% carbon (Ref 14, p.219).

Tensile strength data and HRC hardness numbers for AISI type H12 steel illustrated by the graph (Ref 8, p.461), were used to develop formulas expressing Brinell hardness – tensile strength relationships (Appendix 5, Tables 5.16A and 5.16B):

$$\sigma = 616 \times \text{HB} - 41759 \quad (5.31)$$

$$\sigma = 496 \times \text{HB} \quad (5.32)$$

Linear regression formula (5.31) provides 93.7–99.4% accuracy in calculating tensile strength. The correlation coefficient is 0.9951 (Appendix 5, Table 5.16A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (5.32) provides 90.2–97.7% accuracy in calculating tensile strength (Appendix 5, Table 5.16B), which is less accurate than formula (5.31). The use of these formulas is limited to Brinell hardness range of 225–515 HB.

Tungsten-type steels

Historically, tungsten steels were the first high-alloy steels used for hot-work tooling. Currently, there are six standard grades: AISI types H21 to H26. They contain from 9 to 19% tung-

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sten and moderate amounts of chromium (from 2 to 4% for the majority of grades) and vanadium (from 0.25 to 1.25%). Tungsten types, like chromium types, are medium-carbon steels containing 0.22–0.55% of carbon.

Tungsten type steels have greater hot hardness than any class of hot-work steels and, therefore, have excellent resistance to softening and washing of dies during operations at elevated temperatures. Applications of these steels include extrusion dies for brass, bronze, and steel; hot-press dies, drawing and hot-swaging dies; shear blades and punches (Ref 14, p.234).

Information on mechanical properties was available only for AISI type H21 steel in the form of graphs showing relationships between strengths (tensile and yield) versus HRC hardness (Ref 8, p.462).

AISI Type H21 (UNS T20821) steel

H21 steel is produced to a range of 8.50–10.00% tungsten, 3.00–3.75% chromium, 0.30–0.60% vanadium, 0.15–0.40% manganese, 0.15–0.50% silicon, and 0.26–0.36% carbon (Ref 14, p.219). The machinability rating of this steel is 40–50% of that for the water-hardening tool steels (Ref 8, p.457).

Tensile strength data and HRC hardness numbers for AISI type H21 steel, illustrated by the graph (Ref 8, p.462), were used to develop formulas expressing Brinell hardness – tensile strength relationships (Appendix 5, Tables 5.17A and 5.17B):

$$\sigma = 530 \times \text{HB} - 7144 \quad (5.33)$$

$$\sigma = 510 \times \text{HB} \quad (5.34)$$

Linear regression formula (5.33) provides 94.6–99.8% accuracy in calculating tensile strength. The correlation coefficient is 0.9960 (Appendix 5, Table 5.17A), indicating a strong linear relationship between tensile strength and Brinell hardness.

Statistical formula (5.34) provides 93.0–99.5% accuracy in calculating tensile strength (Appendix 5, Table 5.17B), which is slightly less accurate than formula (5.33). The use of these formulas is limited to Brinell hardness range of 245–480 HB.

Molybdenum-type steels

As a result of wartime shortages of tungsten, a few grades of molybdenum hot-work steels were developed. The properties of these steels were intermediate to the chromium and tungsten hot-work tool steels, but gradually the use of molybdenum steels has declined. Currently, only AISI type H42 (UNS T20842) steel is available and used as an alternative to the tungsten type tool steels when cost is considered. H42 steel contains nominally 5% molybdenum, 6% tungsten, 4% chromium, and 2% vanadium. H42 grade is produced to a range of 0.55–0.70% carbon and available in several carbon ranges (Ref 14, pp.219, 240).

1.5.7. High-speed steels

High-speed steels have dual destinies: they were developed to make cutting tools first, but today high-speed steels are also used to make various parts.

The high-speed steels are designated as group **M** and group **T** steels in the AISI classification system, depending on the major alloying elements: molybdenum or tungsten. In addition, there is a number that follows either the **M** or the **T**. That number does not have any special significance other than to distinguish one from another. Group **M** steels constitute greater than 95% of all high-speed steel produced in the United States. Group **M** and group **T** high-speed steels are equivalent in performance; the main advantage of the group **M** steels is approximately 40% lower initial cost than that of group **T** steels (Ref 7, p.759).

Molybdenum high-speed steels

Molybdenum high-speed steels count up to twenty grades, from M1 to M62. They can be divided into two subgroups, one based primarily on molybdenum additions with limited tungsten (the molybdenum subgroup), and the other based on molybdenum plus substantial tungsten addition (the molybdenum-tungsten subgroup) (Ref 14, p.253).

The molybdenum subgroup includes the M1 and M7 steels with the same amount of molybdenum (8.20–9.20%) and tungsten (1.40–2.10%), and the M10 steel containing slightly less molybdenum (7.75–8.50%) and no tungsten.

The molybdenum-tungsten subgroup includes the M2, M3, and M4 steels, which contain 4.50–5.50% Mo (M2, M4 steels) and 4.75–6.50% Mo (M3 steel). Tungsten content varies: 5.50–6.75% (M2), 5.00–6.75% (M3), and 5.25–6.50% (M4).

Twelve molybdenum high-speed steels (M30 to M48) include modifications with cobalt, ranging from 4.50–5.50% (M30) to 11.00–12.25% (M44).

All molybdenum high-speed steels contain substantial amount of vanadium, ranging from 0.95–1.35% (M42) to 3.75–4.50% (M4). These steels belong to the high-carbon category, ranging from 0.75–0.85% C (M30) to 1.42–1.52% C (M48). Those steels with higher carbon and vanadium contents generally offer improved abrasion resistance.

The maximum hardness that can be obtained for the molybdenum high-speed steels varies with compositions. For those with carbon contents under 1.0%, that is, types M1, M2, M10, M30, M33, M34, M35, and M36, maximum hardness is 65 HRC. For higher carbon contents (1.0–1.4% C), that is, types M3, M4, and M7, maximum hardness is about 66 HRC. Maximum hardness of the higher-carbon cobalt-containing steels, that is, types M41, M42, M43, M44, and M46, is 69–70 HRC (Ref 7, p.759).

Molybdenum-type steels like M1, M2, and M3 are used for manufacturing various cutting tools, such as twist drills, reamers, taps, single point lathe cutters, and milling cutters. M7 and M10 steels are used for blanking and trimming dies, shear blades, thread rolling dies, broaches, and punches (Ref 16, p.446). Cutting tools made of the M40 series of molybdenum steels exhibit top efficiency on difficult-to-machine aerospace materials, such as titanium alloys and nickel-base alloys (Ref 14, p.285).

The machinability rating for the M2 and M7 steels is about 60% and for the other M-type steels is 35–45% of that for the water-hardening tool steels (Ref 8, p.466).

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Tungsten high-speed steels

Tungsten high-speed steels include seven standard grades: T1–T15. Grades T1, T2, T4, T5, and T6 contain 17–21% tungsten; grades T8 and T15 contain 12–15% tungsten. Other alloying elements are chromium (3.75–5.00%), vanadium (0.80–5.25%), silicon (0.15–0.40%), and manganese (0.10–0.40%). All grades, except T1, contain molybdenum (0.40–1.25%). Cobalt in the amount of 4.25–13.00% is present in five grades only. T1 and T2 steels are produced without cobalt.

Group T high-speed steels containing cobalt have greater red hardness and good wear resistance, but slightly less toughness than those steels without cobalt. Applications of these steels include single point tools, milling cutters, drills, taps and reamers, gear cutters, broaches, hot forming punches and dies, blanking dies, slitters, trim dies, powder compacting dies, cold extrusion punches, thread rolling dies, ball and roller bearings, saw blades, and woodworking tools (Ref 8, p.463).

Concluding Remarks on Tool Steels

1. Tool steels are designated according to the AISI/UNS identification number and divided into seven major groups: water-hardening, shock-resisting, cold-work, mold, low-alloy special purpose, hot-work, and high-speed tool steels.

2. Currently, there are 75 standard grades of tool steels, including:

- 3 grades of water-hardening steel
- 6 grades of shock-registering steel
- 17 grades of cold-work steel
- 7 grades of mold steel
- 2 grades of low-alloy special-purpose steel
- 13 grades of hot-work steel
- 27 grades of high-speed steel

3. Study of the tensile strength – Brinell hardness relations conducted by the author, resulted in developing 17 statistical and 17 linear regression formulas. These formulas are summarized in Table 1.5.

4. Strength-to-hardness ratios in statistical formulas for the majority of tool steels are ranging from 502–523. For some grades of tool steel the strength-to-hardness ratios are ranging from 474 (oil-hardening tool steel O1) to 496 (hot-work tool steel H12).

5. High accuracy of statistical formulas for calculating tensile strength is obtained through multiplication of the Brinell hardness number by the corresponding strength-to-hardness ratio.

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6. The correlation coefficients range from 0.9615–0.9990 indicating that linear regression formulas provide high accuracy in calculating tensile strength versus Brinell hardness.

7. The applications of statistical and linear regression formulas are limited to Brinell hardness ranges shown in this table.

8. Machinability rating for the molybdenum high-speed steels is about 35–45% of that for the water-hardening tool steels, except M2 and M7 steels, which have a rating of about 60%.

9. Maximum hardness of the high-carbon cobalt-containing high-speed steels, that is, types M41, M42, M43, M44, and M46, is 69–70 HRC.

10. Tungsten high-speed steels containing cobalt have greater hot hardness and higher wear resistance than those tungsten-type steels without cobalt.

11. Molybdenum-base and tungsten-base high-speed steels are equivalent in performance; the main advantage of the group **M** steels is approximately 40% lower initial cost than that of group **T** steels

Table 1.5. Formulas for calculating tensile strength versus Brinell hardness

Category of Tool Steel	AISI (UNS) Grades	Brinell hardness range, HB	Statistical Formula	Linear Regression Formula	Correlation Coefficient
Water-hardening steel	W1 (T72301)	225–460	$\sigma = 523 \times \text{HB}$	$\sigma = 379 \times \text{HB} + 47330$	0.9615
Shock-resisting steel	S1 (T41901)	210–605	$\sigma = 517 \times \text{HB}$	$\sigma = 543 \times \text{HB} - 11459$	0.9890
Shock-resisting steel	S2 (T41902)	225–560	$\sigma = 494 \times \text{HB}$	$\sigma = 631 \times \text{HB} - 50131$	0.9929
Shock-resisting steel	S5 (T41905)	210–635	$\sigma = 521 \times \text{HB}$	$\sigma = 561 \times \text{HB} - 19646$	0.9951
Shock-resisting steel	S7 (T41907)	205–615	$\sigma = 510 \times \text{HB}$	$\sigma = 553 \times \text{HB} - 19876$	0.9978

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Table 1.5 continued

Oil-hardening steel	O1 (T31501)	235–480	$\sigma = 474 \times \text{HB}$	$\sigma = 546 \times \text{HB} - 26657$	0.9806
Oil-hardening steel	O2 (T31502)	225–540	$\sigma = 503 \times \text{HB}$	$\sigma = 545 \times \text{HB} - 15192$	0.9987
Oil-hardening steel	O7 (T31507)	290–550	$\sigma = 477 \times \text{HB}$	$\sigma = 593 \times \text{HB} - 51470$	0.9959
Air-hardening steel	A2 (T30102)	225–520	$\sigma = 485 \times \text{HB}$	$\sigma = 552 \times \text{HB} - 25062$	0.9986
Air-hardening steel	A6 (T30106)	480–615	$\sigma = 565 \times \text{HB}$	$\sigma = 572 \times \text{HB} - 3689$	0.9720
Mold steel	P6 (T51606)	225–375	$\sigma = 489 \times \text{HB}$	$\sigma = 510 \times \text{HB} - 6106$	0.9980
Mold steel	P20 (T51620)	255–545	$\sigma = 516 \times \text{HB}$	$\sigma = 543 \times \text{HB} - 11173$	0.9980
Low-alloy special-purpose steel	L2 (T61202)	210–545	$\sigma = 503 \times \text{HB}$	$\sigma = 560 \times \text{HB} - 22467$	0.9971
Low-alloy special-purpose steel	L6 (T61206)	195–545	$\sigma = 509 \times \text{HB}$	$\sigma = 579 \times \text{HB} - 26083$	0.9959
Hot-work steel	H11, H13	225–560	$\sigma = 502 \times \text{HB}$	$\sigma = 555 \times \text{HB} - 19290$	0.9990
Hot-work steel	H12 (T20812)	225–515	$\sigma = 496 \times \text{HB}$	$\sigma = 616 \times \text{HB} - 41759$	0.9951
Hot-work steel	H21 (T20821)	245–480	$\sigma = 510 \times \text{HB}$	$\sigma = 530 \times \text{HB} - 7144$	0.9960

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Cutting Tool Materials

The cutting tool materials for machining of steels are high-speed steels, cemented carbides, cermet, ceramics, and polycrystalline cubic boron nitride.

2.1. High-speed steels

According to Metals Handbook, “High-speed steels are so named primarily because of their ability to machine materials at high cutting speeds. They are complex iron-base alloys of carbon, chromium, vanadium, molybdenum, or tungsten, or combinations thereof, and in some cases substantial amounts of cobalt. The carbon and alloy contents are balanced at levels to give high attainable hardening response, high wear resistance, high resistance to the softening effect of heat, and good toughness for effective use industrial cutting operations” (Ref 3, p.51).

High-speed steels are able to maintain high hardness (often referred to as “hot” or “red” hardness) at elevated temperatures: 52 HRC at 1000 °F (540 °C) and 48 HRC at 1100 °F (590 °C).

2.1.1. Brief history of high-speed steels development

The earliest cutting tool materials used for chip removal operations were high-carbon steels. Among these was a special grade developed by Robert Mushet, who in 1868 added tungsten to this type of steel. The composition of this unique grade, marketed as “R. Mushet’s Special Tool Steel,” consisted of 2% carbon, 2.5% manganese, 7% tungsten, 0.5% chromium, and 1.1% silicon. This steel had a remarkable capacity to harden during air-cooling after forging or heating and is regarded as the first high-speed steel (Ref 14, p.4).

In the period from 1894 to 1898, Fred Taylor and Maunsel White at the Bethlehem Steel Corporation discovered that high-temperature heating (much higher than typically applied at that time) and subsequent air cooling of chromium-tungsten steels could produce and maintain exceptional hardness when machining at high speeds, even at “red heat.” This discovery became beneficial to tool steels used for high-speed machining; it established the basis for modern high-speed alloy development, processing, and application. By 1910, production and use of the high-speed steel containing 18% tungsten, 4% chromium, and 1% vanadium (18-4-1) was firmly established. The 18-4-1 steel was commercially adopted and became a foundation for tungsten-based, high-speed steels.

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Shortages of tungsten during World War II urged the development and commercial acceptance of the high-speed steels containing molybdenum as the major alloying element. Since then, the group M of high-speed steels has been established.

The groups T and M have effectively the same performance, but the molybdenum high-speed steels are much more widely used than the tungsten high-speed steels because of cost advantages (Ref 14, p.251).

Another major high-speed steel improvement was made when more vanadium and carbon were added. Such additions formed large amounts of very hard vanadium carbides, which greatly increase abrasion resistance. This discovery led to production of much better quality tools for cutting purposes. More recently, new methods of manufacture of high-speed steels, such as vacuum arc remelting and powder processing, produced high quality and uniformity in composition and microstructure.

Surface-modification heat treatments such as gas carburizing and nitriding have long been applied to high-speed steels. The most recent developments include carburizing and nitriding in vacuum and plasmas, and the application of thin ceramic layers such as titanium nitride by chemical (CVD) and physical (PVD) vapor deposition techniques.

As described in Chapter 1, section 1.5.7, there are 27 high-speed steel grades currently available: twenty M-type grades, and seven T-type grades.

2.1.2. High-speed steel applications

High-speed steels are used for single-point cutting tools and multipoint cutting tools.

Single-point cutting tools are referred to as turning tools, cutoff tools, or inserts. They have only one cutting surface or edge in contact with the work material at the given time. Such tools are used for turning, threading, boring, and planing, and most are mounted in a tool holder, which is made of some type of alloy steel. High-speed steels for turning tools only are described in this book.

Multipoint cutting tools are referred to as drills, reamers, taps, end mills, face mills, broaches, hobs, and circular saws.

Turning tools

Selection of the high-speed steel grades for turning tools depends on the group of steels being cut, the machining parameters (cutting speed, depth of cut, and feed rate), the cutting fluids, and the workholding devices.

M2 and M3 (class 2) grades are recommended for:

- Carbon steels with the hardness range of 85–275 HB
- Alloy steels with the hardness range of 175–275 HB
- Austenitic stainless steels with the hardness range of 135–185 HB
- Martensitic stainless steels (except AISI types 440 series) with the hardness range of 135–275 HB

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- Ferritic stainless steels with the hardness range of 135–185 HB
- Precipitation-hardening stainless steels with the hardness range of 150–200 HB T15, M33, M41, M42, M43, M44, M46, and M47 grades are recommended for:
- High-carbon steels with the hardness range of 275–375 HB
- Alloy steels with the hardness range of 275–425 HB
- Austenitic stainless steels with the hardness range of 225–275 HB
- Martensitic stainless steels (except AISI types 440 series) with the hardness range of 275–425 HB
- Martensitic stainless steels (AISI types 440 series) with hardness of 225 HB to 52 HRC (512 HB)
- Precipitation-hardening stainless steels with the hardness range of 275–440 HB

2.1.3. Chemical composition of high-speed steels

Chemical composition of high-speed steel grades recommended for turning and face milling are summarized in Table 2.1 (Ref 14, p.252).

Table 2.1. Chemical composition, %*

AISI (UNS) grades	C	Mn	Si	Cr	Mo	W	V	Co
M2 (T11302)	0.78-0.88	0.15-0.40	0.20-0.45	3.75-4.50	4.50-5.50	5.50-6.75	1.75-2.20	
M3 (T11323)	1.15-1.25	0.15-0.40	0.20-0.45	3.75-4.50	4.75-6.50	5.00-6.75	2.75-3.75	
M7 (T11307)	0.97-1.05	0.15-0.40	0.20-0.55	3.50-4.00	8.20-9.20	1.40-2.10	1.75-2.25	
M33 (T11333)	0.85-0.92	0.15-0.40	0.15-0.50	3.50-4.00	9.00-10.00	1.30-2.10	1.00-1.35	7.75-8.75
M41 (T11341)	1.05-1.15	0.20-0.60	0.15-0.50	3.75-4.50	3.25-4.25	6.25-7.00	1.75-2.25	4.75-5.75
M42 (T11342)	1.05-1.15	0.15-0.40	0.15-0.65	3.50-4.25	9.00-10.00	1.15-1.85	0.95-1.35	7.75-8.75
M43 (T11343)	1.15-1.15	0.20-0.40	0.15-0.65	3.50-4.25	7.50-8.50	2.25-3.00	1.50-1.75	7.75-8.75
M44 (T11344)	1.10-1.20	0.20-0.40	0.30-0.55	4.00-4.75	6.00-7.00	5.00-5.75	1.85-2.20	11.00-12.25
M46 (T11346)	1.22-1.30	0.20-0.40	0.40-0.65	3.70-4.20	8.00-8.50	1.90-2.20	3.00-3.30	7.80-8.80
M47 (T11347)	1.05-1.15	0.15-0.40	0.20-0.45	3.50-4.00	9.25-10.00	1.30-1.80	1.15-1.35	4.75-5.25
T15 (T12015)	1.50-1.60	0.15-0.40	0.15-0.40	3.75-5.00	1.00 max	11.75-13.00	4.50-5.25	4.75-5.25

* 0.30% Ni (max) and 0.03% S (max)

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2.1.4. *Effect of alloying elements*

Alloying elements are listed in the same order, as they are presented in Table 2.1: **C** (carbon), **Mn** (manganese), **Si** (silicon), **Cr** (chromium), **Mo** (molybdenum), **W** (tungsten), **V** (vanadium), and **Co** (cobalt). Effects of these alloying elements on the mechanical properties (Ref 3, pp.52, 53; Ref 14, pp.283, 287; Ref 17, pp.78, 79) are described below.

Carbon

Within an overall alloy composition, each alloying element requires different amounts of carbon in order to be fully utilized in carbide formations. Table 2.1 shows that the carbon content ranges from a low of 0.78% to a high of 1.60%. Although the carbon content of a given grade is fixed within narrow limits, variations within these limits may cause changes in mechanical properties and cutting performance. As the carbon concentration is increased, the working hardness and the elevated temperature hardness become higher, and the number of hard, stable, complex carbides increases. These complex carbides contribute much to the wear resistance and abrasion resistance of the high-speed steels.

Manganese

The manganese content ranges from 0.15 to 0.60%, which is not high in concentration. Higher manganese content increases brittleness and the danger of cracking upon quenching.

Silicon

The silicon content ranges from 0.15 to 0.65%, but the majority of high-speed steel grades shown in Table 2.1 are produced with silicon up to 0.45%. Increasing the silicon content from 0.15 to 0.45% gives a slight increase in maximum attainable tempered hardness and a concurrent slight decrease in toughness. Some manufacturers produce at least one grade with silicon up to 0.65% (M46), but this level of silicon content requires a lower austenitizing temperature than does a lower silicon level in the same grade. In general, however, the silicon content is kept below 0.45% on most grades.

Chromium

Chromium is always present in the amounts ranging from 3.5 to 5.0% and its role is to provide hardenability and to increase cutting efficiency. Chromium in the amount of 4.0% gives the best compromise between hardness and toughness. Chromium also reduces oxidation and scaling during heat treatment.

Molybdenum

Molybdenum is always present in the amounts ranging from 3.25 to 10.00% in molybdenum grades, and in a small amount of 1.0% in the T15 grade. Molybdenum forms double carbide with

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iron and carbon. The melting point of the molybdenum grades is somewhat lower than that of the tungsten grades, and thus they require a lower hardening temperature and have a narrower hardening range. The molybdenum-type high-speed steels are tougher than the tungsten-type high-speed steels, but the hot hardness is slightly lower. Molybdenum promotes resistance to tempering. Cutting efficiency is increased as the molybdenum content is increased.

Tungsten

All grades shown in Table 2.1 contain tungsten in the amounts ranging from 1.15 to 7.00% in molybdenum grades, and 11.75 to 13.00% in the T15 grade. Tungsten improves hot hardness and significantly contributes to wear resistance. Tungsten and molybdenum perform similar functions and are more or less interchangeable on an atomic basis. On a weight basis, 1% molybdenum is taken to be equivalent to 1.6–2.0% tungsten.

Vanadium

Vanadium is always present in high-speed steels usually between 0.95 and 3.30% in molybdenum grades, and from 4.50 to 5.25% in the T15 grade (Table 2.1). The main effect of vanadium is to produce the very hard vanadium carbide particles, which significantly increase wear resistance and, to a lesser extent, hot hardness. Grades with intermediate vanadium contents (2.0–3.0%) are suited for finishing and roughing cuts on both hard and soft steels. An increase in vanadium has little effect on the toughness. For this reason, high-speed steel tools containing 4–5% vanadium are used when high toughness, exceptional hot hardness, and wear resistance are required.

Cobalt

Cobalt contributes significantly to the hot hardness, and is a major alloying element that attains high hardness of 67 HRC after tempering. The degree of hot hardness is proportional to the cobalt content. Cobalt additions up to 5% have the greatest effect, and additions above 8% have negligible effect. Although cobalt-containing steels are more brittle than no-cobalt grades, they provide better performance on hardened steels that are machined with deep cuts at high speeds.

Nickel

Nickel is usually considered as undesirable element in high-speed steels, and its content is held at the lowest possible level, which should not exceed 0.30%, as stated in the notice (*) for Table 2.1.

Sulfur

Sulfur, in normal concentration of 0.03% or less, has no effect on the properties of high-speed steel. The addition of 0.10–0.17% sulfur progressively improves the machinability of the high-speed steels themselves when used as work pieces to make large milling cutters with accurately shaped and dimensioned teeth and good surface.

Concluding Remarks on High-speed Steels

1. High-speed steels are designated according to the AISI / UNS identification number and divided into two groups: molybdenum (M-type) and tungsten (T-type).
2. No single grade of high-speed steels can satisfy all cutting tool requirements.
3. M2 and M3 (class 2) grades are used for turning of carbon, alloy, and stainless steels with hardness of 85–275 HB.
4. T15, M33, M41, M42, M43, M44, M46, and M47 high-speed steels are used for turning of carbon, alloy, and stainless steels with hardness of 225 HB to 52 HRC.
5. There are ten molybdenum-base grades (M2, M3, M7, M33, M41 to M47) and one tungsten-base grade (T15) that are currently used for turning of steels.

2.2. Cemented carbides

As the name implies, cemented carbide is a sintered material whose components are carbide compounds of refractory metals and a metallic binder matrix. Cemented carbides belong to a class of hard and wear-resistant materials in which the hard carbide particles are bound together, or cemented, by a soft and ductile metal binder. Cemented carbides are typical powder-metallurgical products. Although the terms cemented carbides are widely used in the United States, these materials are better known as hard metals internationally.

2.2.1. Brief history of cemented carbides development

Cemented carbides, or hard metals, are the most commonly used cutting tool material for more than eighty years.

Development of the modern cemented carbides is associated with the name of Karl Schroeter (Germany). His first cemented carbide was a sintered product of a compacted powder of tungsten monocarbide (WC) mixed with 10% of a metal of the iron group, which also includes cobalt and nickel. The first experiments by Schroeter were performed with nickel as a binder metal. The nickel-bound products were superior to all previously known carbides. After the replacement of nickel by cobalt (Co), cemented carbides became more superior. The powder mixture of WC-Co was compacted and sintered at a temperature close to the melting point of cobalt. Melted cobalt has good wetting properties for the carbide grains and during solidification creates dense, practically pore-free materials.

The sintering procedure developed by Karl Schroeter became the foundation for production of cemented carbides. First, commercial cemented carbide product containing 6% cobalt was marketed under the trade name Widia in Germany in 1926. Large-scale production of cemented WC-Co materials, which originally contained 4–13% Co, were marketed under the trade names

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Carbology (USA) and Ardoloy (England). Carbology, a division of the General Electric Company, started production of cemented carbides in the United States in 1928.

Most of the subsequently introduced hard metals were the modifications of Schroeter's compositions, which were produced by replacing either a portion or all of the tungsten carbide (WC) with other carbides, in particular titanium carbide (TiC), tantalum carbide (TaC), and molybdenum carbide (Mo_2C). It was Dr. Schwarzkopf who first recognized that solid solutions of more than one carbide are superior to individual carbides as a basis of hard metals.

In 1931, the Friedrich Krupp A.G. company started production of multicarbide product (trade name Widia X) containing approximately 84% WC, 10% TiC, and 6% Co.

The first American WC-TiC composition (69% WC, 31% TiC, 10% Co) was introduced in 1932 under the trade name Carbology Grade 831.

In 1938, Philip M. McKenna, founder of Kennametal Inc., patented WC-TiC-Co compositions, which were produced by forming the solid carbide solutions in a molten nickel bath. This so-called menstruum process was used to produce WC-TiC-TaC-Co and other multicarbide materials (Ref 18, pp.5–8).

Over the years, the basic WC-Co material has been modified to produce a variety of cemented carbide grades, which are used in a wide range of applications, including metal cutting, mining, construction, rock drilling, metal forming, structural components, and wear parts. Approximately 50% of all carbide production is used for metal cutting applications (Ref 3, p.71).

Significant improvement of the cutting tool performance is associated with hard coatings applied to cemented carbide inserts to resist specific wear mechanisms, extend tool life, and boost productivity. Currently, there are two commercially successful coatings: chemical vapor deposition (CVD), which was introduced in the early 1970s, and physical vapor deposition (PVD), which was introduced in the early 1980s. In the year 2000, more than 70% of all cemented carbide inserts were coated by CVD, PVD, or combination of both (Ref 19, pp.98–107).

In CVD process, inserts are heated to approximately 980 °C (1800 °F). The most popular CVD coatings are titanium carbide (TiC), titanium nitride (TiN), titanium carbonitride (TiCN), and alumina (Al_2O_3). CVD coating combines several layers, which are about 5–20 μm thick. Such coating withstands different types of tool wear. For example, in a TiN / TiC / Al_2O_3 multilayer, the TiC layer resists abrasive flank wear and Al_2O_3 protects the rake face of a cutting insert from crater wear.

Moderate-temperature chemical vapor deposition coatings (MT-CVD) are a further development in CVD technology. In MT-CVD process, the leading coating is TiCN, which can be applied at 850 °C (1560 °F). Lower deposition temperatures and shorter coating cycles result in enhancing the strength of the cutting edges and making coated inserts suitable for interrupted cutting.

The PVD process is produced at relatively low temperatures (500 °C, or 930 °F) and allows manufacturers to coat sharp insert edges. Indexable inserts coated by this process are essential in milling, drilling, threading, and cutoff operations as well as for effective machining of low-carbon steels, which generate long chips when cutting. Typical PVD coatings are TiN, TiC, TiCN, and TiAlN (titanium aluminum nitride). Combinations of “soft” coatings, such as molybdenum disulfide (MoS_2), and “hard” coatings, such as TiN or TiAlN, are suitable for dry machining: the hard coating provides wear resistance, whereas the soft, more lubricious outer layer expedites chip flow.

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2.2.2. Classification systems for cemented carbides

There is no universally accepted system for classifying cemented carbides. The systems adapted by tool manufacturers and users are based on the U.S. Industry code and ISO (International Organization for Standardization) code.

U.S. Industry code

In 1942, Oscar Strand, tool supervisor of the Buick Motor Division of General Motors, produced a simple classification, known as Buick code, that arranged nearly 100 grades derived from 10 manufacturers under only 14 symbols (TC-1 to TC-14). Then, the letter T disappeared and the Buick code became the U.S. Industry code, also known as C-grade system, which is divided into four categories.

- Carbide grades for machining of ferrous, nonferrous, and nonmetallic material:
 - C1.....Roughing
 - C2.....General-purpose machining
 - C3.....Finishing
 - C4.....Precision finishing
- Carbide grades for machining of steel:
 - C5.....Roughing
 - C6.....General-purpose machining
 - C7.....Finishing
 - C8.....Precision finishing
- Nonmachining, wear-resisting grades:
 - C9.....No shock
 - C10.....Light shock
 - C11.....Heavy shock
- Nonmachining, impact-resisting grades:
 - C12.....Light
 - C13.....Medium
 - C14.....Heavy

The C1 through C4 grades are straight tungsten carbides bonded with cobalt; they mostly vary in cobalt content and grain size. They are widely used for machining cast irons, high temperature alloys, nonferrous metals including titanium alloys, and abrasive nonmetallic materials. Hardness increases and toughness decreases in going from C1 to C4. The C2 grades provide a good compromise in properties and categorized as “general purpose” for machining of the abovementioned materials.

The C5 through C8 grades are multcarbide materials, which contain mainly various combinations of tungsten carbide, titanium carbide, tantalum carbide, and niobium carbide bonded with cobalt. Grades C5 through C8 are recommended for machining steels because they provide better

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crater resistance than the C1 to C4 grades. Hardness increases and toughness decreases in going from C5 to C8. The C6 grades are for general-purpose applications (Ref 2, p.14-7).

Nonmachining carbide grades (C9 through C14) are not discussed here, because this book focuses on machining of steels.

C-grade system does not require the use of trade names for identifying specific carbide grades and, therefore, simplifies tool application. At the same time, this system does not reflect the carbide properties that significantly influence selection of the proper carbide grade. It should be noted that the various manufacturers' carbide grades listed under the same industry code (C5, C6, etc.), are not necessarily equivalent in their physical and mechanical properties.

ISO classification

In 1964, the International Organization for Standardization developed a classification of cemented carbides, based on ISO Recommendation R513 "Application of Carbides for Machining by Chip Removal." All machining grades produced by various manufacturers are divided into three color-coded groups.

- Highly alloyed tungsten carbide grades, which are multi carbide grades (letter P, blue color) for machining of steels. P-grades designation: P01, P10, P20, P30, P40, and P50.
- Alloyed tungsten carbide grades, which are multicarbide grades (letter M, yellow color, generally with less TiC than in the P-grades) for machining of steels, nickel-base super alloys, and ductile cast irons. M-grades designation: M10, M20, M30, and M40.
- Straight tungsten carbide grades (letter K, red color) for machining of gray cast iron, nonferrous metals, and nonmetallic materials. K-grades designation: K01, K10, K20, K30, and K40.

In each letter category, low designation numbers are for high speeds and light feeds; higher numbers are for slower speeds and/or heavier feeds. Increasing designation numbers imply increasing toughness and decreasing hardness and wear resistance of the cemented carbide materials.

Multicarbide grades P01 through P50 and the M10 through M40 grades contain various combinations of tungsten carbide, titanium carbide, tantalum carbide, and niobium carbide bonded with cobalt. These grades and the C5 through C8 grades are similar by chemical compositions, microstructures, properties, and applications.

Currently, the most commonly used cemented carbides for turning of steels are the compositions containing WC-TiC-(Ta, Nb)C-Co. Tantalum carbide is often added as (Ta, Nb)C because the chemical similarity between TaC and NbC makes their separation expensive (Ref 20, p.855).

The amount of each component (wt %) in a given grade within the same group of application (C-grade system and ISO classification) depends on the cutting tool manufacturers. Such grades do not necessary equal in performance. Selection of the appropriate grade depends on the type of steel to be machined, its hardness, machining operations, cutting parameters, and the recommendations by the carbide tool manufacturers.

2.2.3. Properties of multcarbide grades

Selection of multcarbide grades for a given metal cutting application is based on their physical and mechanical properties, among which hardness, compressive strength, and transverse rupture strength are usually available from the carbide manufacturers' catalogs.

Hardness

Hardness of cemented carbides is measured by the Rockwell A-scale indentation test using the 120° sphericoconical diamond indenter at the 60 kgf applied load (HRA), and by the Vickers indentation test using a square-based pyramidal diamond indenter with included face angles of 136° at variable loads, ranging mostly from 1gf to 10 kgf (HV).

Typical hardness of cemented carbides used in machining of steel ranging from 88 to 92 HRA, or from 1100 to 1600 HV respectively. HRA hardness numbers and respective HV hardness numbers were adopted from Ultra-met catalog (Ref 21, p.19).

The author developed linear regression equations to convert HRA numbers into HV numbers. Linear regression analysis and equations are given in Appendix 1, Tables 1.20–1.26.

Hardness of cemented multcarbide grades is most strongly influenced by the cobalt content, the grain size, purity, and chemical composition. Hardness of WC-TiC-Co products increases with increasing titanium carbide (TiC) content, but can be decreased by corresponding increases of cobalt (Co) content. For example, the hardness of such composition containing 10% TiC and 6% Co is 1650 HV; the hardness of composition with 10% TiC and 8% Co is 1530 HV; and the composition with 23% TiC and 6% Co is 1700 HV, as shown in Figure 2.1 (Ref 18, p.161).

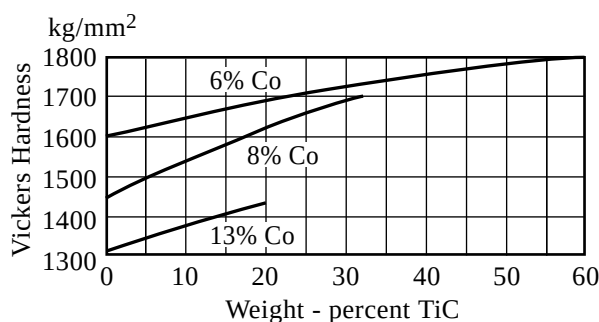


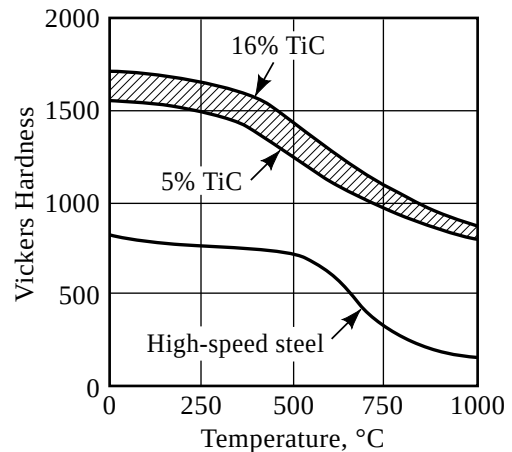
Fig. 2.1 Hardness of WC-TiC-Co products as a function of Co and TiC contents

The hot hardness of WC-TiC-Co compositions increases with increasing TiC content and remains much higher than that for high-speed steel. The hot hardness of compositions with 5% TiC and 16% TiC at 250 °C (480 °F) temperature is 1500 HV and 1670 HV respectively. The hot hardness of the composition with 16% TiC at 1000 °C (1830 °F) is 860 HV, which is about the same as the hardness of high-speed steel at room temperature, as shown in Figure 2.2 (Ref 18, p.162).

The hot hardness of cemented carbides is a true indication of their resistance to plastic deformation in metal-cutting operations.

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Fig. 2.2 Hot Hardness of WC-TiC-Co products as a function of temperature.



Compressive strength

Cemented carbides under compression at room temperature deform elastically but not plastically, which means that the material fractures immediately as soon as the elastic limit is surpassed. The compressive strength of WC-Co compositions increases with increasing cobalt content, reaching the maximum strength (8.4×10^5 psi or 5800 MPa) at about 4% cobalt and then decreases considerably to the minimum strength (4.4×10^5 psi or 3000 MPa) at about 27% Co (Ref 18, p.141).

Compressive strength of WC-TiC-Co compositions with 6% Co decreases from 7.1×10^5 psi (4900 MPa) to 5.3×10^5 psi (3650 MPa) when TiC content increases from 7.5% to 60%, as shown in Figure 2.3 (Ref 18, p.161).

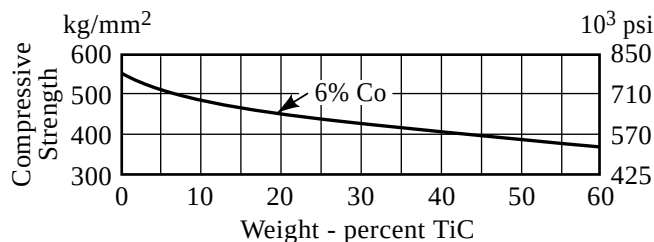


Fig. 2.3 Compressive strength of WC-TiC-Co products as a function of Co and TiC contents

Permanent deformation of WC-TiC-Co (78% WC, 16% TiC, and 6% Co) under compressive loads at 1000 °C (1830 °F) and 1100 °C (2010 °F) are 0.1% and 0.8% respectively, compared with 0.3% and 1.8% permanent deformation of WC-Co composition containing 94% WC and 6% Co (Ref 18, p.147).

The compressive strengths of cemented carbides are greater than those of most other materials. Typical values of compressive strength at room temperature range from 5×10^5 psi (3450 MPa) to 106 psi (6900 MPa). Like hardness, the compressive strength decreases monotonically with increasing temperature: the rate of decrease depends on the composition and the microstructure.

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Tables 2.2 and 2.3 illustrate compressive strength of some typical multcarbide grades at various temperatures and their chemical compositions.

As can be seen from Table 2.2 and Table 2.3, the compressive strengths of these grades

Table 2.2. Compressive strength of multcarbide grades, psi (MPa)

Multcarbide grade	Temperature, °F (°C)		
	1470 (800)	1650 (900)	1830 (1000)
73WC-22(Ti, Ta, Nb)C-5Co	3.5×10^5 (2400)	2.9×10^5 (2000)	2.2×10^5 (1500)
80WC-12(Ti, Ta, Nb)C-8Co	2.8×10^5 (1900)	2.2×10^5 (1500)	1.5×10^5 (1050)
86WC-8(Ti, Ta, Nb)C-6Co	2.2×10^5 (1500)	1.7×10^5 (1170)	1.3×10^5 (900)
86WC-2TaC-12Co	2.0×10^5 (1400)	1.4×10^5 (950)	0.8×10^5 (550)

Table 2.3. Chemical composition of the same grades

Multcarbide grade	Chemical composition, wt %			
	WC	(Ti, Ta, Nb)C	TaC	Co
73WC-22(Ti, Ta, Nb)C-5Co	73	22	—	5
80WC-12(Ti, Ta, Nb)C-8Co	80	12	—	8
86WC-8(Ti, Ta, Nb)C-6Co	86	8	—	6
86WC-2TaC-12Co	86	—	2	12

decrease with increasing temperature and cobalt content. Variations in multcarbide compositions also affect compressive strength. All compositions are characterized by medium grain size of WC (Ref 3, p.78).

Transverse rupture strength

In metal cutting applications, the relationship between transverse rupture strength (TRS) and turning operation has not been established. However, interrupted cutting shows that cemented carbides with higher TRS provide better impact resistance than those with lower TRS as the cutting inserts reenter into a workpiece.

Transverse rupture strength of WC-TiC-Co compositions decreases continuously with increasing titanium carbide content. The higher the cobalt content, the higher the transverse rupture strength. This relationship remains for a wide range of titanium carbide content, as shown in Figure 2.4 (Ref 18, p.161).

A similar relationship applies to ternary WC-TiC-TaC solutions. For example, TRS of 71WC-12.5TiC-12TaC-4.5Co carbide grade is 200 ksi, or 1380 MPa, and TRS of 72WC-8TiC-11.5TaC-8.5Co grade is 250 ksi, or 1720 MPa (Ref 3, p.79). A decrease in titanium carbide from 12.5% to 8.0% and an increase in cobalt content from 4.5% to 8.5% increases TRS from 200 ksi to 250 ksi.

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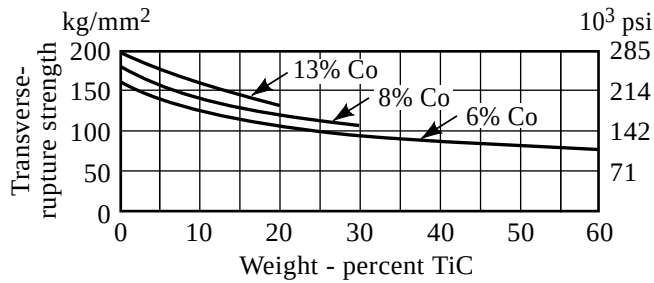


Fig. 2.4 TRS of WC-TiC-Co products as a function of Co and TiC contents

Multicarbides WC-TiC-(Ta, Nb)C-Co typically contain: 5–10% cobalt (Co), 4–25% titanium carbide (TiC), and up to 25% tantalum-niobium carbides (Ta, Nb)C combined. TiC reduces the tendency of WC to diffuse into steel chip surfaces. TaC and NbC improve strength, resist to crater formation, and provide thermal shock resistance. The grain size of carbide particles ranges from 0.8 to 2 μm . Transverse rupture strengths of such compositions range from 150 to 300 ksi (Ref 22, p.82).

Transverse rupture strength of cemented carbides sintered under high heat and pressure (HIP – Hot Isostatic Process) can increase by 25–75 percent and be as high as 550,000 psi (Ref 23, p.49).

2.2.4. Applications

Cemented carbide cutting tools are used in the form of coated indexable inserts of various shapes, sizes, and chip-breaker geometries. The cutting tool manufacturers produce dozens of different coated cemented carbide grades designed for turning of carbon, alloy, stainless, and tool steels with a broad range of hardness. Selection of proper grades depends on class or group of steel and type of machining operation: roughing, semiroughing, and finishing.

The size of this book restricts us from covering all of the cutting tool manufacturers and their numerous carbide grades for turning of steels. Therefore, the author selected only three major cutting tool manufacturers: Kennametal® (the author worked for this company), Kyocera, and Sandvik Coromant.

Kennametal® offers six PVD coated carbide grades and eleven CVD coated carbide grades for turning all types of steels (Ref 24, p.A28–A30). As an example, a few carbide grades are described below:

- PVD TiAlN coated KC5010 grade defined as C3 and C4 by C-grade system, P10 to P20 and M10 to M20 by ISO classification. Recommended for finishing and general machining of carbon, alloy, stainless, and tool steels. This grade is also suitable for heat-resistant alloys, titanium alloys, cast irons, and nonferrous alloys.
- CVD TiCN / TiC / Al_2O_3 / TiN coated KC9040 cobalt-enriched grade defined as C5 and C6 by C-grade system and P30 to P40 by ISO classification. Used for heavy roughing operation on all types of steels when the cutting edge strength is critical. This type of coating provides prolonged tool life.

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- CVD TiCN / Al₂O₃ / TiN coated KC9110 cobalt-enriched grade defined as C3 and C7 by C-grade system and P10 to P20 by ISO classification. Recommended for finishing and medium operations on most steels including ferritic and martensitic stainless steels. Thick coating layers provide outstanding abrasion resistance and crater wear resistance. The smooth coating provides good resistance to built-up edge and micro-chipping and produces excellent surface finishes.

Kyocera is offering ten CVD-coated carbide grades, among which four grades are used for turning of carbon and alloy steels and two grades are used for turning of stainless steels (Ref 25, p.20). As an example, a few carbide grades are described below:

- MT-CVD TiCN / Al₂O₃ / TiN coated CA5505 grade defined as C6 to C8 by C-grade system and P01 to P20 by ISO classification. Recommended for high-speed finishing of carbon and alloy steels. TiCN and Al₂O₃ layers provide long tool life.
- MT-CVD TiCN / Al₂O₃ / TiN coated CA5535 grade defined as C5 and C6 by C-grade system and P20 to P40 by ISO classification. Designed for heavy interrupted cutting and high feed machining of carbon and alloy steels. TiCN and Al₂O₃ layers provide a good balance of wear resistance and toughness.
- MT-CVD TiCN / Al₂O₃ / TiN coated CA6525 grade defined as M10 to M30 by ISO classification. Designed for interrupted general cutting of stainless steels. Strong Al₂O₃ film with TiCN layer provides good wear resistance and reduces notching and burrs.

Sandvik Coromant is offering four PVD coated carbide grades and eight CVD coated carbide grades for turning all types of steels (Ref 26, p. A408–A410). As an example, a few carbide grades are described below:

- PVD coated GC1025 micro-grain carbide defined as C6 to C8 by C-grade system, as P25 (P10–P35) and M15 (M10–M25) by ISO classification. Recommended for finishing of low-carbon and stainless steels when excellent surface finish or sharp cutting action is required. Great resistance to thermal shock also makes this grade suitable for interrupted cuts.
- CVD coated GC2015 carbide grade defined as C6 and C7 by C-code, as P25 (P20–P30) and M15 (M05–M25) by ISO classification. Used for finishing and light roughing of carbon and stainless steels. A substrate, which handles high temperatures and wear-resistant coating, make this grade a first choice for continuous cuts at moderate to high cutting speeds.
- CVD coated GC2025 carbide grade defined as M25 (M15–M35) by ISO classification. Used for semifinishing and roughing of austenitic and duplex stainless steels at moderate cutting speeds. Good resistance to thermal shock and mechanical shock provides excellent edge security for interrupted cuts.

Concluding Remarks on Cemented Carbides

1. Cemented carbides are classified by two codes: U.S. Industry code (also known as C-grade system) and ISO (International Organization for Standardization) classification.

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2. Chemical vapor deposition (CVD), moderate-temperature chemical vapor deposition (MT-CVD), and physical vapor deposition (PVD) significantly improve cutting tool performance.

3. Currently, more than 70% of all cemented carbide inserts are coated by CVD, PVD, or a combination of both.

4. Cemented carbide grades C8 through C5 (C-grade system) and equivalent grades P01 through P50 and the M10 through M40 (ISO classification) are recommended for machining of steels. These grades contain various combinations of tungsten carbide, titanium carbide, tantalum carbide, and niobium carbide bonded with cobalt. They are similar by chemical compositions, microstructures, properties, and applications.

5. Coated carbide grades exhibit longer tool life, and much better abrasion and heat resistance than uncoated carbides. Therefore, higher cutting speeds and feeds are applied when turning of steel.

2.3. Cermets

Cermet is a name, which combines parts of two words: ceramic and metal. Cermets are the powder metallurgy products consisting of ceramic particles bonded with a metal. Typical ceramic particles are titanium carbide (TiC), titanium nitride (TiN), and titanium carbonitride (TiCN). The binder includes nickel, cobalt, and molybdenum. Carbide particles provide wear resistance, and metallic binder provides the toughness.

2.3.1. Brief history of cermets development

The first cermets, containing titanium carbide / molybdenum carbide solid solutions with 15% nickel as binder, were manufactured in Germany in 1929. They were used for finish turning of steel (Ref 3, p.91). Applications of these cermets were limited because they exhibit low strength and high brittleness. But the interest in titanium carbide continued due to the lower cost of raw material (titanium oxide) and its availability. Advantage in higher hardness and oxidation resistance of titanium carbide, compared to that of tungsten carbide, accelerated research and development.

In the mid 1950s, the poor wettability of TiC–Ni composition was improved with the addition of molybdenum (Mo) or molybdenum carbide (Mo₂C) to the nickel binder phase. Improved cermets performed well at high speeds and high temperatures, but were unable to withstand interrupted cutting.

Another improvement of cermet properties came in 1973, when Japanese manufacturers began adding titanium nitride (TiN) to the hard-particle portion of the composition in order to create a cermet with a finer microstructure. This modification resulted in manufacturing indexable inserts with improved high-temperature strength and oxidation resistance (Ref 27, p.27).

In the mid 1970s, tantalum carbide and niobium carbide were added to the basic TiC–Ni composition to improve tool life (Ref 28, p.74).

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Cutting performance of cermets was improved after development of titanium-molybdenum-carbon-nitrogen and titanium-tungsten-carbon-nitrogen compounds with binders containing nickel, molybdenum, cobalt, or a combination thereof (Ref 3, p.91).

Cermet development covered two areas: binders and coatings. Manufacturers have developed fine-grain compositions with more binders to give the cutting tools greater toughness and heat resistance. However, increased binders content reduces hardness and wear resistance. In order to retain wear resistance, coated cermets were developed. The commonly-used coatings are titanium nitride (TiN), titanium carbonitride (TiCN), and titanium aluminum nitride (TiAlN) applied by moderate-temperature chemical vapor deposition (MT-CVD) and physical vapor deposition (PVD).

Current cermet indexable inserts are available in a variety of geometries and more successfully used for finishing and light roughing applications.

Coolant is a major concern. Coated cermets can run with coolant, but the users must watch for thermal shock. In general, coolant is not recommended for rough cuts, but it is recommended for finishing operations (Ref 28, p.82).

2.3.2. Classification systems for cermets

The U.S. Industry code and ISO classification system for cemented carbides can be used to designate cermet grades. Cermets for machining of steel are mostly C8, C7, and C6 grades (U.S. Industry code), which are equivalent to P01, P10, P20, M10, and M20 grades (ISO classification).

2.3.3. Properties of cermets

The manufacturers of cutting tool materials treat the compositions and properties of their grades as proprietary information. Currently used cermets are based on titanium carbonitride grades because of their higher wear resistance, hardness, and transverse rupture strength in comparison to titanium carbide base cermets.

Hardness

The hardness of titanium carbonitride cermets is approximately comparable to that of cemented carbides. However, cermets' hardness at the same elevated temperatures is higher. It permits cermets to run at a higher cutting speed and hold the size of flank wear longer than most cemented carbides.

Transverse rupture strength

The strength of cermets is about 15–25% lower than the strength of cemented carbides. Therefore, depths of cut and feeds (feed rate and feed per tooth) have to be selected more conservatively, especially in roughing operations when compared to cemented carbides.

Other properties

The key properties of cermets are chemical stability, oxidation resistance, and resistance to

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cutting edge built-up. These properties allow cermets to be used on cutting carbon, alloy, and stainless steels with negligible crater wear and built-up edge. Cermets are more effective than cemented carbides in high-speed machining, because they provide higher resistance to deformation. In near-to-shape operations where surface finish is critical, cermets provide a finishing cut so smooth that grinding can be eliminated.

2.3.4. Applications

Cermet cutting tools are used in the form of indexable inserts manufactured by the process similar to that of cemented carbides. This similar manufacturing process results in production of indexable inserts of various shapes, sizes, and chip-breaker geometries customary for cemented carbide inserts.

Cermet cutting tools are capable of operating at higher cutting speeds than cemented carbides, and are suitable for various machining operations, especially for turning.

The main reason for the application of cermet cutting tools in turning is their long and consistent tool life over a wide range of cutting speeds (Ref 3, p.95). There are many cermet grades recommended by major cutting tool manufacturers for turning of steel.

As an example, some of the currently used cermets are described on the following page:

- KT315 is a Kennametal® three-layered PVD titanium nitride – titanium carbonitride – titanium nitride (TiN / TiCN / TiN) coated grade defined as C3 and C7 by C-grade system, as P05 and P10, M05, and M10 by ISO classification. Recommended for high-speed finishing and medium machining of most carbon, alloy, and stainless steels. This grade provides long and consistent tool life and produces excellent surface finishes (Ref 24, p.A30).
- PV7020 is a Kyocera PVD TiN / TiAlN (titanium nitride – titanium aluminum nitride) coated super micro-grain cermet defined as C8 to C6 grades by C-code and P01 to P20 grades by ISO specification. Recommended for superior performance at medium roughing and finishing of alloy and stainless steels. This grade provides high wear resistance at high-speed machining (Ref 25, pp.18, 19).
- GC1525 is a Sandvik Coromant PVD coated grade defined as C6 and C7 by C-code, P15 (P05–P25) and M10 (M05–M15) by ISO definition. This cermet has very high wear resistance and good edge toughness. Used for finishing and semi-finishing of low-carbon and alloy steels when good surface quality is demanded at medium to high cutting speeds; also recommended for finishing of stainless steels at high speeds and relatively low feeds (Ref 26, pp. A408–A410).

Concluding Remarks on Cermets

1. Classification systems for cermets are similar to that for cemented carbides.

2. Currently used cermets are based on titanium carbonitride grades because of their higher wear resistance, hardness, and transverse rupture strength in comparison to titanium carbide base cermets.

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3. Cermet cutting tools are capable of operating at higher cutting speeds than cemented carbides, and are suitable for finishing and semiroughing operations mostly without coolant.
4. Due to high resistance to plastic deformation and built-up edges, cermets produce excellent surface finishes.

2.4. Ceramics

There are two major groups of ceramics used in metalcutting: one group is based on aluminum oxide (Al_2O_3) and another group is based on silicon nitride (Si_3N_4). Ceramic inserts are produced either by hot pressing or sintering. Hot pressing involves heating the powder in a die, along with the simultaneous application of a high uniaxial pressure. Sintering can be either a heat process without pressure or hot isostatic pressing (HIP) process when heat is applied under pressure (30,000 psi) in a chamber containing nitrogen, argon, or helium. HIP-process reduces porosity in the substrate (Ref 29, p.46).

2.4.1. Brief history of ceramics development

Al_2O_3 – based ceramic was considered for certain machining applications as early as 1905, and patents pertaining to this technology were issued in England and Germany around 1912. However, the strength and toughness of these ceramic tools were inadequate for commercial applications. In the United States, the work in this area began as early as 1935. In the 1960s, the development of hot pressing and hot isostatic pressing resulted in stronger and more reliable ceramics based on polycrystalline α - Al_2O_3 (white ceramic) with a variety of sintering aids and compositions. These tools were primarily used for the high-speed finishing of cast iron and steel for the automotive industry or for the slow-speed machining of extremely hard forged alloy steels in the steel roll industry. Improvements in the thermo-mechanical properties have been made in the late 1960s when Japanese researchers added titanium carbide (TiC) to an Al_2O_3 matrix. Typical aluminum oxide and titanium carbide ceramics (Al_2O_3 -TiC) contain 25–40% TiC. They are often called black ceramics due to their color from titanium carbide (Ref 3, p.98).

Alumina-zirconia (Al_2O_3 - ZrO_2) ceramic with traces of tungsten carbide was introduced by the Carboly Systems Department of General Electric in the early 1980s. This alloyed ceramic provides higher toughness and thermal shock resistance than monolithic Al_2O_3 . The three popular compositions contain 10%, 25%, and 40% ZrO_2 ; the remainder is Al_2O_3 . The increase of ZrO_2 content provides higher toughness but decreases the hardness (Ref 3, pp.98, 99).

The incorporation of silicon carbide (SiC) whiskers in the amount of 25–45% into an Al_2O_3 matrix with subsequent hot pressing results in a composite with significantly higher fracture toughness: about twice as that of monolithic Al_2O_3 . The whiskers are small fibers of single-crystal SiC about 0.5–1 μm (20–40 $\mu\text{in.}$) in diameter and 10–80 μm (400–3200 $\mu\text{in.}$) long. A higher thermal conductivity and a lower coefficient of thermal expansion of whisker-reinforced ceramics provide higher thermal shock resistance in comparison with Al_2O_3 (Ref 3, p.99).

Cutting tool materials of silicon nitride base exhibit excellent high-temperature mechanical properties and resistance to oxidation and thermal shock. Both transverse rupture strength and frac-

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ture toughness of Si_3N_4 are higher than these for $\text{Al}_2\text{O}_3\text{-TiC}$. The thermal conductivity of Si_3N_4 is approximately two times higher than that of $\text{Al}_2\text{O}_3\text{-TiC}$, whereas the coefficient of thermal expansion is about one-half that of $\text{Al}_2\text{O}_3\text{-TiC}$. These thermal properties provide much lower sensitivity to temperature changes and improve thermal-shock resistance. However, these properties are not utilized until the difficulties in sintering pure Si_3N_4 have been solved. Various metal oxides and nitrides have been found as effective sintering aids. The most commonly used additives to Si_3N_4 are aluminum oxide (Al_2O_3), aluminum nitride (AlN), and silica (SiO_2). A system made up of Al_2O_3 and Si_3N_4 is named Sialon due to its chemical formula: SiAlON (Ref 3, p.100).

Multiple coatings of TiC-TiN or $\text{Al}_2\text{O}_3\text{-TiC}$ on Si_3N_4 and SiAlON substrates have been developed to minimize chemical interactions when machining steels at high speeds.

2.4.2. Properties of ceramics

Ceramics' hot hardness and oxidation resistance reduce the amount of tool wear at high cutting tool temperatures. These properties make ceramic cutting tools suitable for high-speed machining of various work materials including difficult-to-machine metals.

In comparison with cemented carbides, ceramics have lower transverse rupture strength and fracture toughness (Table 2.4). Therefore, the applications of ceramic cutting tools are limited to certain machining conditions.

Table 2.4. Room-temperature properties of ceramics and tungsten carbides (Ref 3, p.101)

Cutting tool material	Hardness, HRA	Transverse rupture strength		Fracture toughness	
		ksi	MPa	ksi in.	MPa m
Al_2O_3	93–94	70–100	500–700	3.2–4.1	3.5–4.5
$\text{Al}_2\text{O}_3\text{-TiC}$	94–95	90–120	600–850	3.2–4.1	3.5–4.5
$\text{Al}_2\text{O}_3\text{-ZrO}_2$	93–94	100–130	700–900	4.5–7.3	5.0–8.0
$\text{Al}_2\text{O}_3\text{-SiC}$	94–95	80–110	550–750	4.1–7.3	4.5–8.0
Si_3N_4	92–94	100–150	700–1050	5.5–7.7	6.0–8.5
SiAlON	93–95	100–125	700–900	4.1–5.5	4.5–6.0
WC-Co alloys	91–93	180–300	1250–2100	9.1–11.4	10.0–13.5

2.4.3. Applications

Ceramic cutting tools are used mostly in turning and boring. Cutting tools are produced in the form of indexable inserts, similar to cemented carbides and cermets.

High hot hardness and chemical inertness make ceramic inserts suitable for high-speed finish machining. The higher thermal shock resistance of the tougher ceramics, such as sialon and silicon carbide whisker reinforced aluminum oxide ($\text{SiC-Al}_2\text{O}_3$), makes them suitable for use with cutting fluids in most applications.

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As an example, some of the currently used ceramics are described below:

- KY1615 is a Kennametal® uncoated, aluminum oxide and titanium carbide ($\text{Al}_2\text{O}_3\text{-TiC}$) black ceramic grade defined as C4 and C8 by C-grade system. A great combination of toughness and wear resistance makes this ceramic grade suitable for machining alloy steels, martensitic stainless steels, and tool steels hardened to 60 HRC (Ref 24, p.A31).
- KY4400 is a Kennametal® PVD titanium nitride coating over aluminum oxide and titanium carbonitride ceramic. This grade defined as C4 and C8 by C-grade system. Recommended for finish machining of steels with the hardness greater than 45 HRC. Where possible, dry machining is recommended (Ref 24, p.A31).
- A65 is a Kyocera aluminum oxide and titanium carbide ($\text{Al}_2\text{O}_3\text{-TiC}$) black ceramic grade. Designed for semiroughing and finishing of steel, cast iron, and hardened materials (Ref 25, p.26).
- A66N is the A65 substrate ceramic with titanium nitride coating. This grade is tougher and more wear resistant than uncoated A65 grade. The coating layer prevents chipping. The anti-oxidation of this grade makes it resistant to crater wear and results in longer tool life. Used for machining of hardened materials in many applications (Ref 25, p.26).
- CC6050 is a Sandvik Coromant coated, mixed ceramic grade based on aluminum oxide (Al_2O_3) with the addition of titanium carbide (TiC). The high hot hardness and good toughness make this grade suitable for continuous finishing on hardened steels of 45–65 HRC (Ref 26, pp.A407, A412).

Concluding Remarks on Ceramics

1. Classification systems for ceramics are similar to that for cemented carbides.
2. Currently-used ceramics are based on aluminum oxide (white ceramic), aluminum oxide with titanium carbide (black ceramic), aluminum oxide reinforced with silicon carbide whiskers, silicon nitride, and sialon.
3. Ceramics based on silicon nitride provide higher transverse rupture strength and fracture toughness than other types of ceramics.
4. Ceramic tools are most commonly used for turning of cast irons and high-temperature alloys.
5. Cutting tools made of aluminum oxide with titanium carbide ($\text{Al}_2\text{O}_3\text{-TiC}$) and aluminum oxide with titanium carbonitride ($\text{Al}_2\text{O}_3\text{-TiCN}$) are used primarily for turning of hardened steels.
6. High hot hardness and chemical inertness make ceramic inserts suitable for high-speed finish machining. The higher thermal shock resistance of the tougher ceramics such as sialon (SiAlON) and silicon carbide whisker reinforced aluminum oxide ($\text{SiC-Al}_2\text{O}_3$) allows the use of cutting fluids in most applications.

2.5. Polycrystalline cubic boron nitride

Polycrystalline cubic boron nitride (PCBN) is next to diamond on the hardness scale. It is used in the manufacturing industry as a superhard abrasive tool and as a cutting tool. As a cutting tool, PCBN is most commonly used for the machining of hardened steels, tool steels, hard cast irons, and hardfacing alloys.

2.5.1. Brief history of PCBN development

Boron (B) and nitrogen (N) can form the boron nitride compound, which is a soft hexagonal substance like hexagonal carbon (graphite). Just as hexagonal carbon can be transformed into cubic carbon (diamond), hexagonal boron nitride (HBN) can be transformed into cubic boron nitride (CBN). Polycrystalline cubic boron nitride (PCBN) is produced by sintering many individual crystals of CBN together to produce a larger polycrystalline mass (Ref 3, p.105).

In the late 1950s, cubic boron nitride was first synthesized from hexagonal boron nitride under high-pressure and high-temperature process (Ref 30, p.22).

Applications of PCBN cutting tools have changed dramatically since their introduction in the 1970s. To meet machining requirements for a variety of work materials, especially for hardened steels, cast irons, and powder metals, various grades of PCBN inserts were developed and are now available (Ref 31, p.86). Coated PCBN inserts improve tool life and provide excellent adhesion between the coating and the PCBN substrate interface (Ref 32, p.42).

2.5.2. Properties of PCBN

Solid PCBN cutting tool materials exhibit an exceptionally high value of thermal conductivity: 58 Btu / ft x h x °F (100 W / m x °K), which is about the same as C-8 or K10 tungsten carbides have, and about 4–5 times higher than that for ceramic cutting tool materials. PCBN is thermally stable in the machining of ferrous workpiece materials. Thermal conductivity of PCD (polycrystalline diamond) cutting tool materials is about five times higher than that of PCBN, but cannot be used in the machining of ferrous workpiece materials. PCD reacts with ferrous material at moderate temperatures and is subject to graphitization.

Selected mechanical properties of PCBN, PCD, and other tool materials are summarized in the following table.

As can be seen from Table 2.5, fracture toughness of solid PCBN tools is higher than that of ceramic tools. Solid PCBN also exhibits higher compressive strength than sialon. It means that PCBN tools can take heavier cuts than ceramic tools.

Among the variables that influence a PCBN grade performance are the percentage of cubic boron nitride (CBN) particles and grain size. The CBN content of the majority grades ranges from 45 to 90 percent. Grain sizes vary from 8 μm (315 $\mu\text{in.}$) for coarse-grain tools, to submicron size for fine-grain tools. A high concentration of particles increases compressive strength, toughness, and wear resistance, and provides higher thermal conductivity. Therefore, tools with high CBN content are suitable for roughing applications. Low-content CBN tools are less thermally conductive and retain an adequate amount of heat in the workpiece. The heat softens the workpiece at the

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Table 2.5. Properties of PCBN and other tool materials (Ref 3, p.107)

Cutting tool material	Knoop hardness, GPa	Compressive strength		Fracture toughness	
		ksi $\times 10^6$	GPa	ksi in.	MPa m
Al ₂ O ₃	16	0.580	4.00	2.12	2.33
Al ₂ O ₃ -TiC	17	0.653	4.50	3.01	3.31
SiAlON	13	0.508	3.50	4.55	5.00
Tungsten carbide (K10)	13	0.653	4.50	9.83	10.80
Solid PCBN (Amorite)	28	0.551	3.80	5.73	6.30
Layered PCBN	28	0.515	3.55	3.37	3.70
Solid PCD	50	0.687	4.74	6.27	6.89
Layered PCD	50	1.102	7.60	8.01	8.80

cutting zone, allowing the tool to consume less energy to separate the chip from the parent material. Tools containing lower amounts of CBN are recommended for finishing operations (Ref 30, p.22).

2.5.3. Applications

Polycrystalline boron nitride cutting tool materials from different manufacturers vary in particle size distribution, binder materials, and cubic boron nitride (CBN) grain concentrations. Therefore, the mechanical properties of PCBN materials are not the same. However, there are two broad categories of applications:

1. Rough machining of ferrous materials with hardness range of 45–65 HRC, and with depths of cut between 0.020 in. (0.5 mm) and 0.315 in. (8 mm).
2. Finish machining of hardened tool steels and surface-hardened cast irons, with depths of cut below 0.020 in. (0.5 mm), mostly 0.008 in. (0.2 mm)

Rough machining of hard ferrous materials requires a high concentration of CBN grains, whereas finishing operations are performed more effectively when PCBN cutting tools have a lower concentration of CBN grains (Ref 3, p.111).

PCBN cutting tools are used mostly in hard turning. They are produced in the form of indexable inserts, similar to cemented carbides, cermets, and ceramics.

High-speed tool steels and cold work tool steels at the hardness range of 45 HRC to 65 HRC are machined with PCBN cutting tools when it is necessary to refurbish components or correct a mistake. The refurbishing of rolls in the steel or paper industries or removal of worn threads from thread rolling dies is also performed with PCBN cutting tools. Such tools are also used for rough and finish machining of bearing steels in the hardened state (Ref 3, pp.113, 114).

As an example, some of the currently used PCBN grades are described below:

- KB5625 is a Kennametal® low-CBN content tip with titanium aluminum nitride (TiAlN) PVD coating grade defined as C4 and C8 by C-code. The PCBN tip is brazed onto a carbide insert. Used for roughing and finishing of bearing steel and various tool steel types with hardness greater than 45 HRC (Ref 24, p.A31).

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- KB9610 is a Kennametal® low-CBN content grade. The solid PCBN insert with a titanium-nitride–aluminum oxide–titanium carbonitride CVD coating withstands crater wear. This PCBN grade is defined as C4 and C8 by C-code. Recommended for the precision machining of bearing steel and various tool steel types with hardness greater than 48 HRC (Ref 24, p.A31).
- KBN510 is a Kyocera PCBN grade with good wear resistance and crack resistance. Used for semiroughing and finishing turning of steels with hardness greater than 45 HRC. The uniform matrix of CBN and binder provide maximum heat dispersion (Ref 25, pp.14, 29).
- KBN525 is a Kyocera PCBN grade used for general and interrupted machining of steels with hardness greater than 45 HRC at high speeds and high feed rates. The uniform matrix of CBN and binder provide maximum heat dispersion (Ref 25, pp.14, 29).
- CB7020 is a Sandvik Coromant high performance polycrystalline cubic boron nitride grade. Recommended for continuous and light interrupted cuts in hardened steel (Ref 26, p.A412).

Concluding Remarks on PCBN

1. PCBN is next to diamond on the hardness scale. Polycrystalline cubic boron nitride is produced by sintering many individual crystals of cubic boron nitride (CBN) and a binder together to make a larger polycrystalline mass.
2. As a cutting tool, PCBN is most commonly used for the machining of hardened steels, tool steels, hard cast irons, and hardfacing alloys.
3. The CBN content of the majority grades ranges from 45 to 90 percent. Grain sizes vary from coarse-grain (315 μm .) to submicron fine-grain. Tools with high-CBN content are used for rough machining, and tools with low-CBN content are used for finish machining.
4. PCBN cutting tools are produced in the form of indexable inserts, similar to cemented carbides, cermets, and ceramics.
5. PCBN cutting tools are most commonly used for machining various types of tool steels with the hardness ranging from 45 to 65 HRC and hardened cast irons.
6. Hard turning of ferrous alloys are performed with tipped and solid PCBN tools from various cutting tool manufacturers.

Chapter 3

Machining Recommendations

Turning is a machining process for generating external surfaces by the action of a cutting tool on a rotating workpiece, usually in a lathe (Ref 3, p.135). Among various basic operations performed on turning equipment (boring, facing, cutoff, and threading), only straight turning is discussed in this chapter, because this operation is characterized by higher metal removal rate and, subsequently, by higher power consumption. The value of required machining power is the key element for maximizing productivity of cutting.

For almost three decades, the Machining Data Handbook (Ref 1 and Ref 2) has remained a reliable source of technical information on the cutting speed data versus depth of cut, feed rate, cutting tool material, and the workpiece materials.

The speeds and feeds for the various operations presented in Machining Data Handbook were obtained from the many sources and represent a tool life of 30–60 minutes applicable for carbide indexable inserts (Ref 1, p. XV). This handbook provides machining data when turning of steel with HSS, cemented carbide, cermet, and ceramic cutting tools. Unfortunately, machining data for turning of hardened tool steels with polycrystalline cubic boron nitride cutting tools were not included in this handbook.

Machining parameters for turning of steel with coated carbide, cermet, and ceramic cutting tools were adopted from this handbook and analyzed.

The machining recommendations (Ref 1, pp.1.3–1.33; 1.59–1.78) should be considered only as starting cutting parameters that require certain adjustments in accordance with today's metalcutting technology. It means that the final selection of cutting speeds and feeds can be made according to the experience with similar parts, the recommendations by the cutting tool manufacturers, or from production trials.

For the last two decades, the metalcutting industry has made significant progress. New cutting tool materials have been developed. In the year 2000, more than 70% of all cemented carbide inserts were coated by chemical vapor deposition (CVD) and physical vapor deposition (PVD). Cermets, ceramics, and polycrystalline cubic boron nitride cutting tools are becoming more popular when machining hardened steels.

Major cutting tool manufacturers, such as Kennametal®, SANDVIK Coromant, Iscar Metals Inc., and others, offer today a wide variety of carbide, cermet, ceramic, and polycrystalline cubic boron nitride grades for indexable inserts of numerous designs. Therefore, contemporary cutting tools are able to machine steels at higher speeds and feeds than the cutting tools used decades ago.

Chapter 3

3.1. Depth of cut and feed rate

The major machining parameters of turning are: the cutting speed, depth of cut, and feed rate. Usually, depth of cut and feed rate are conservative parameters predetermined by the type of operation: roughing, semiroughing, and finishing. The range of typical depth of cuts and feed rates are as follows (Ref 33, p.76):

- Roughing: depth of cut 0.200–0.600 in., feed rate 0.020–0.060 ipr
- Semiroughing: depth of cut 0.080–0.200 in., feed rate 0.008–0.020 ipr
- Finishing: depth of cut 0.020–0.080 in., feed rate from 0.004–0.010 ipr.

Starting machining recommendations for turning with single-point cutting tools are adopted from Machining Data Handbook for carbon, alloy, stainless, and tool steels. Depth of cuts and feed rates are the same for each type of steel and depend on the cutting tool material, type of operations, and the hardness of a workpiece.

3.1.1. Depth of cut and feed rate when turning with coated carbide tools

The following depth of cuts and feed rates for carbon, alloy, stainless, and tool steels with a wide range of hardness (85–425) HB are adopted from Machining Data Handbook (Ref 1, pp.1.3–1.33):

- Roughing: depth of cut is 0.300 in. and feed rate is 0.020 ipr
- Semiroughing: depth of cut is 0.150 in. and feed rate is 0.015 ipr
- Finishing: depth of cut is 0.040 in. and feed rate is 0.007 ipr.

3.1.2. Depth of cut and feed rate when turning with cermet and ceramic tools

The following depth of cuts and feed rates for carbon, alloy, stainless, and tool steels are adopted from Machining Data Handbook (Ref 1, pp.1.59–1.78):

Hardness range of (85–325) HB

- Roughing: depth of cut is 0.300 in. and feed rate is 0.015 ipr
- Semiroughing: depth of cut is 0.150 in. and feed rate is 0.010 ipr
- Finishing: depth of cut is 0.040 in. and feed rate is 0.005 ipr.

Hardness range of (325–425) HB

- Roughing: depth of cut is 0.300 in. and feed rate is 0.012 ipr
- Semiroughing: depth of cut is 0.150 in. and feed rate is 0.008 ipr
- Finishing: depth of cut is 0.040 in. and feed rate is 0.004 ipr.

Hardness range of (45–48) HRC

- Roughing: depth of cut is 0.300 in. and feed rate is 0.008 ipr
- Semiroughing: depth of cut is 0.150 in. and feed rate is 0.006 ipr
- Finishing: depth of cut is 0.040 in. and feed rate is 0.003 ipr.

Hardness range of (48–56) HRC

- Semiroughing: depth of cut is 0.150 in. and feed rate is 0.006 ipr
- Finishing: depth of cut is 0.040 in. and feed rate is 0.003 ipr.

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Concluding Remarks on the Depth of Cut and Feed Rate

1. Depth of cut and feed rate are conservative parameters predetermined by the type of operation: roughing, semiroughing, and finishing.
2. Depth of cut values are set in accordance with the type of operations:
 - 0.300 in. for roughing
 - 0.150 in. for semiroughing
 - 0.040 in. for finishing.
3. Feed rate values are set in accordance with the type of operations, the cutting tool material, and the hardness of steel.
4. When turning of steel with coated carbide tools, the feed rates are:
 - 0.020 ipr for roughing
 - 0.015 ipr for semiroughing
 - 0.007 ipr for finishing.
5. When turning of steel with ceramic and cermet tools, the feed rates are:
 - 0.008–0.015 ipr for roughing
 - 0.006–0.010 ipr for semiroughing
 - 0.003–0.005 ipr for finishing.
6. The lower feed rate values in each range of operation is associated with the higher hardness numbers. Roughing is not used if the hardness of steel exceeds 48 HRC.

3.2. Cutting speeds for carbon steels

The feasibility of using carbon steels depends on whether or not their properties (tensile, yield, and fatigue strengths and impact resistance) and need for heat treatment are suitable for the parts. If required characteristics can be obtained with carbon steel, most users select this steel, which is less costly than other steel (Ref 34, p.56).

Carbon steels are divided into six categories: nonresulfurized low-, medium-, and high-carbon steels; free-machining resulfurized steels; free-machining resulfurized and rephosphorized steels; and nonresulfurized high-manganese steels (greater than 1% Mn).

Tables providing hardness, depth of cut, feed rate, cutting speed, and type of carbon steels are presented throughout this section.

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3.2.1. Low-carbon steels

Low-carbon steels produce long, continuous chips, which will form a built-up edge on indexable insert if a chip breaker doesn't create a sufficient shear angle to curl the chip away from the rake face of the insert. Low cutting speed is another reason for built-up edge, which acts as an extension of the cutting tool, causing changes in part dimensions and rough-machined surfaces. In such cases, the cutting speed should be increased by 15–20% or more, until the machined surface is improved.

Low-carbon steels are ductile and not very resistant to wear. Wear resistance can be improved by increasing the carbon content of the surface (carburizing). Carburizing is produced by heating at an elevated temperature in a controlled, carbon rich atmosphere. Commonly carburized grades are AISI 1015, 1018, and 1020.

Low-carbon steels are machined at slightly different cutting speeds and, therefore, are divided in Group 1 (Table 3.1) and Group 2 (Table 3.2).

Typical roughing, semiroughing, and finishing parameters for steels in Group 1 when turning with coated carbide tools are shown in Table 3.1 (Ref 1, p.1-6).

Table 3.1. AISI 1005, 1006, 1008, 1010, 1012, 1015, 1017, 1020, 1023, and 1025

Brinell hardness HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V_c), sfm	Coated carbide classification, C-grade ⁽¹⁾ / ISO ⁽²⁾
85–125	0.300	0.020	550	C6 / P30
	0.150	0.015	700	C6 / P20
	0.040	0.007	1050	C7 / P10
125–175	0.300	0.020	500	C6 / P30
	0.150	0.015	625	C6 / P20
	0.040	0.007	950	C7 / P10
175–225	0.300	0.020	450	C6 / P30
	0.150	0.015	550	C6 / P20
	0.040	0.007	850	C7 / P10

⁽¹⁾ U.S Industry code. ⁽²⁾ ISO standard 513.

Typical roughing, semiroughing, and finishing parameters for steels in Group 2 when turning with coated carbide tools are shown in Table 3.2.

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Table 3.2. AISI 1016, 1018, 1019, 1021, 1022, and 1026 (Ref 1, p.1-7)

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Coated carbide classification, C-grade / ISO
85–125	0.300	0.020	525	C6 / P30
	0.150	0.015	675	C6 / P20
	0.040	0.007	1025	C7 / P10
125–175	0.300	0.020	500	C6 / P30
	0.150	0.015	625	C6 / P20
	0.040	0.007	950	C7 / P10
175–225	0.300	0.020	450	C6 / P30
	0.150	0.015	550	C6 / P20
	0.040	0.007	850	C7 / P10

The cutting speeds for the low-carbon steels shown in Table 3.1 are 2.4–4.8% higher than those shown in Table 3.2 for the hardness range of (85–125) HB. There is no difference in the cutting speeds for the low-carbon steels with the hardness range of (125–225) HB. The cutting speed increases from roughing to semiroughing and reaches its maximum at finishing operation. The workpiece with higher hardness is machined at lower cutting speeds.

Table 3.3. AISI 1005, 1006, 1008, 1010, 1012, 1015, 1017, 1020, 1023, and 1025

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Ceramic and cermet tool materials
85–125	0.300	0.015	1100	CPA ⁽¹⁾
	0.150	0.010	1500	CPA
	0.040	0.005	2000	CPA
125–175	0.300	0.015	1200	CPA
	0.150	0.010	1400	CPA
	0.040	0.005	1900	CPA
175–225	0.300	0.015	1000	HPC ⁽²⁾
	0.150	0.010	1300	CPA
	0.040	0.005	1700	CPA

⁽¹⁾ Cold pressed aluminum oxide (white ceramics). ⁽²⁾ Hot pressed cermet.

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Typical roughing, semiroughing, and finishing parameters when turning with cermet and ceramic tools are shown in Tables 3.3 (Ref 1, p.1-61) and 3.4 (Ref 1, p.1-62).

Identification of ceramic (CPA) and cermet (HPC) cutting tools and their manufacturers are listed in Machining Data Handbook (Ref 2, p.14-17)

Table 3.4. AISI 1016, 1018, 1019, 1021, 1022, and 1026

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V_c), sfm	Ceramic and cermet tool materials
85–125	0.300	0.015	1050	CPA
	0.150	0.010	1450	CPA
	0.040	0.005	2000	CPA
125–175	0.300	0.015	1150	CPA
	0.150	0.010	1350	CPA
	0.040	0.005	1900	CPA
175–225	0.300	0.015	950	HPC
	0.150	0.010	1250	CPA
	0.040	0.005	1700	CPA

As can be seen from Table 3.3 and Table 3.4, the cutting speed increases from roughing to semiroughing and reaches its maximum at finishing operation. The workpiece with higher hardness is machined at lower cutting speeds. Machining Data Handbook recommends ceramic tools for roughing, semiroughing, and finishing when low-carbon steels are not harder than 175 HB, and ceramic tools for semiroughing and finishing at the hardness range of (175–225) HB. Hot pressed cermet tools are recommended for roughing applications at the hardness range of (175–225) HB.

As can be seen from Table 3.1 through Table 3.4, the cutting speeds for ceramic and cermet tools are about 2 times higher than those for coated carbide tools at the same depth of cuts and the range of hardness, but at lower feed rates: 0.015 ipr versus 0.020 ipr (roughing), 0.010 ipr versus 0.015 ipr (semiroughing), and 0.005 ipr versus 0.007 ipr (finishing).

3.2.2. Resulfurized free-machining low-carbon steels

Resulfurized free-machining steels (AISI 11xx series) contain 0.08–0.33% sulfur and, therefore, have better machinability than other carbon steels of similar carbon and manganese contents. Better machinability means better chip control, higher metal removal rate, longer tool life, and better surface finish quality. All these result in lower costs of using free-machining steels for machining parts.

Resulfurized free-machining low-carbon steels are divided in two groups by their average

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machinability ratings: Group 1 includes grades with 80% average machinability rating, Group 2 includes grades with 90% average machinability rating (higher percentage means better machinability). Ratings are based on AISI 1212 free-machining steel as 100% average machinability.

Typical roughing, semiroughing, and finishing parameters for steels in Group 1 when turning with coated carbide tools are shown in Table 3.5.

Table 3.5. AISI 1108, 1109, and 1110 (Ref 1, p.1-3)

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Coated carbide classification, C-grade / ISO
100–150	0.300	0.020	550	C6 / P30
	0.150	0.015	700	C6 / P20
	0.040	0.007	1050	C7 / P10
150–200	0.300	0.020	575	C6 / P30
	0.150	0.015	700	C6 / P20
	0.040	0.007	1100	C7 / P10

Typical roughing, semiroughing, and finishing parameters for steels in Group 2 when turning with coated carbide tools are shown in Table 3.6.

Table 3.6. AISI 1116, 1117, 1118, and 1119 (Ref 1, p.1-3)

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Coated carbide classification, C-grade / ISO
100–150	0.300	0.020	625	C6 / P30
	0.150	0.015	775	C6 / P20
	0.040	0.007	1200	C7 / P10
150–200	0.300	0.020	650	C6 / P30
	0.150	0.015	800	C6 / P20
	0.040	0.007	1225	C7 / P10

As can be seen from Table 3.5 and Table 3.6, free-machining steels in Group 2 are machined at the cutting speeds 14, 11, and 9% higher (roughing, semiroughing, and finishing operations respectively) than steels in Group 1. The higher cutting speeds are applicable due to better average machinability rating of steels in Group 2.

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Typical roughing, semiroughing, and finishing parameters for steels in Group 1 when turning with ceramic tools are shown in Table 3.7.

Table 3.7. AISI 1108, 1109, and 1110 (Ref 1, p.1-59)

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V_c), sfm	Ceramic tool materials
100–150	0.300	0.015	1100	CPA
	0.150	0.010	1400	CPA
	0.040	0.005	1800	CPA
150–200	0.300	0.015	1200	CPA
	0.150	0.010	1500	CPA
	0.040	0.005	1900	CPA

Typical roughing, semiroughing, and finishing parameters for steels in Group 2 when turning with ceramic tools are shown in Table 3.8.

Table 3.8. AISI 1116, 1117, 1118, and 1119 (Ref 1, p.1-59)

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V_c), sfm	Ceramic tool materials
100–150	0.300	0.015	1300	CPA
	0.150	0.010	1600	CPA
	0.040	0.005	2000	CPA
150–200	0.300	0.015	1500	CPA
	0.150	0.010	1800	CPA
	0.040	0.005	2200	CPA

As can be seen from Table 3.7 and Table 3.8, AISI 1116 to 1119 free-machining steels are machined at the higher cutting speeds than AISI 1108 to 1110 steels. Increase in the cutting speed depends on the hardness and the type of operation:

Brinell hardness range 100–150 HB

- Cutting speed is 18% higher at roughing
- Cutting speed is 14% higher at semiroughing

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- Cutting speed is 11% higher at finishing
- Brinell hardness range 150–200 HB
- Cutting speed is 25% higher at roughing
 - Cutting speed is 20% higher at semiroughing
 - Cutting speed is 16% higher at finishing

As can be seen from Table 3.5 through Table 3.8, the cutting speeds for ceramic tools are about 2 times higher than those for coated carbide tools at the same depth of cuts and the range of hardness, but at lower feed rates: 0.015 ipr vs. 0.020 ipr (roughing), 0.010 ipr vs. 0.015 ipr (semi-roughing), and 0.005 ipr vs. 0.007 ipr (finishing).

3.2.3. Resulfurized and rephosphorized free-machining low-carbon steels

These free-machining low-carbon steels (AISI 12xx series) contain more sulfur (0.10–0.35%) and phosphorus (0.04–0.12%) than AISI 11xx steels. Increased amount of these elements provide better machinability and improve chip control.

AISI 12xx grades are produced as unleaded and leaded steels. There are four unleaded grades (AISI 1211, 1212, 1213, and 1215) and three leaded grades (AISI 12L13, 12L14, and 12L15) containing 0.15–0.35% lead each. The lead enhances the effect of sulfur, permitting increased machining speeds. Lead disperses in steel like microscopic particles, which act as a lubricant preventing built-up edge and helping to break chips.

For machining data on AISI grades 1211 and 1212 when turning with coated carbide tools, refer to the preceding Table 3.6 for the free-machining low-carbon steels.

Typical roughing, semiroughing, and finishing parameters for unleaded steels when turning with coated carbide tools are shown in Table 3.9.

Table 3.9. AISI 1213 and 1215 (Ref 1, p.1-3)

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Coated carbide classification, C-grade / ISO
100–150	0.300	0.020	675	C6 / P30
	0.150	0.015	850	C6 / P20
	0.040	0.007	1300	C7 / P10
150–200	0.300	0.020	725	C6 / P30
	0.150	0.015	900	C6 / P20
	0.040	0.007	1350	C7 / P10

Typical roughing, semiroughing, and finishing parameters for leaded steels when turning with coated carbide tools are shown in Table 3.10.

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Table 3.10. AISI 12L13, 12L14, and 12L15 (Ref 1, p.1-4)

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Coated carbide classification, C-grade / ISO
100–150	0.300	0.020	825	C6 / P30
	0.150	0.015	1025	C6 / P20
	0.040	0.007	1550	C7 / P10
150–200	0.300	0.020	800	C6 / P30
	0.150	0.015	1000	C6 / P20
	0.040	0.007	1500	C7 / P10
200–250	0.300	0.020	750	C6 / P30
	0.150	0.015	925	C6 / P20
	0.040	0.007	1400	C7 / P10

As can be seen from Table 3.9 and Table 3.10, leaded free-machining steels are machined at the higher cutting speeds than unleaded free-machining steels. Increase in the cutting speed depends on the hardness and the type of operation:

Brinell hardness range 100–150 HB

- Cutting speed is 22% higher at roughing
- Cutting speed is 20% higher at semiroughing
- Cutting speed is 19% higher at finishing

Brinell hardness range 150–200 HB

- Cutting speed is 11% higher at roughing, semiroughing, and finishing.

For machining data on AISI grades 1211 and 1212 when turning with ceramic tools, refer to the preceding Table 3.8 for the free-machining low-carbon steels.

Table 3.11. AISI 1213 and 1215 (Ref 1, p.1-59)

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Ceramic tool materials
100–150	0.300	0.015	1500	CPA
	0.150	0.010	1800	CPA
	0.040	0.005	2200	CPA
150–200	0.300	0.015	1600	CPA
	0.150	0.010	1900	CPA
	0.040	0.005	2300	CPA

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Typical roughing, semiroughing, and finishing parameters for unleaded steels when turning with ceramic tools are shown in Table 3.11.

Typical roughing, semiroughing, and finishing parameters for leaded steels when turning with ceramic tools are shown in Table 3.12.

Table 3.12. AISI 12L13, 12L14, and 12L15 (Ref 1, p.1-60)

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V_c), sfm	Ceramic tool materials
100–150	0.300	0.015	1900	CPA
	0.150	0.010	2200	CPA
	0.040	0.005	2600	CPA
150–200	0.300	0.015	1800	CPA
	0.150	0.010	2100	CPA
	0.040	0.005	2500	CPA
200–250	0.300	0.015	1700	CPA
	0.150	0.010	2000	CPA
	0.040	0.005	2400	CPA

As can be seen from Table 3.11 and Table 3.12, leaded free-machining steels are machined at the higher cutting speeds than unleaded free-machining steels. Increase in the cutting speed depends on the hardness and the type of operation:

Brinell hardness range 100–150 HB

- Cutting speed is 27% higher at roughing
- Cutting speed is 22% higher at semiroughing
- Cutting speed is 18% higher at finishing

Brinell hardness range 150–200 HB

- Cutting speed is 13% higher at roughing
- Cutting speed is 11% higher at semiroughing
- Cutting speed is 9% higher at finishing

3.2.4. Medium-carbon steels

Medium-carbon steels produce discontinuous chips, resulting in a finer surface finish compared to low-carbon steels. Cutting forces and tool wear increase as the carbon content and hardness increase. These steels are used when higher strength of parts is required, and heat treatment of such parts provides even greater strength. Medium-carbon steels are among the most widely used steels for machined components.

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Typical roughing, semiroughing, and finishing parameters for the medium-carbon steels when turning with coated carbides are shown in Table 3.13 (Ref 1, pp.1-7, 1-8).

Table 3.13. AISI 1030 to 1039, 1040 to 1046, 1050 to 1055 (16 grades total)

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V_c), sfm	Coated carbide classification, C-grade / ISO
125–175	0.300	0.020	475	C6 / P30
	0.150	0.015	600	C6 / P20
	0.040	0.007	925	C7 / P10
175–225	0.300	0.020	415	C6 / P30
	0.150	0.015	525	C6 / P20
	0.040	0.007	785	C7 / P10
225–275	0.300	0.020	400	C6 / P30
	0.150	0.015	500	C6 / P20
	0.040	0.007	750	C7 / P10
275–325	0.300	0.020	375	C6 / P30
	0.150	0.015	450	C6 / P20
	0.040	0.007	700	C7 / P10
325–375	0.300	0.020	315	C6 / P30
	0.150	0.015	375	C6 / P20
	0.040	0.007	575	C7 / P10
375–425	0.300	0.020	250	C6 / P30
	0.150	0.015	300	C6 / P20
	0.040	0.007	475	C7 / P10

As can be seen from Table 3.13, the way in which the cutting speeds are changing, in relationship with the hardness of steel and the type of operations, are similar to that for low-carbon steels.

For machining data on AISI 1029 medium-carbon grade when turning with coated carbide tools, refer to the preceding Table 3.2 for low-carbon steels.

For machining data on AISI 1029 medium-carbon grade when turning with ceramic and cermet tools, refer to the preceding Table 3.4 for the low-carbon steels.

Typical roughing, semiroughing, and finishing parameters for medium-carbon steels when turning with ceramics and cermets are shown in Table 3.14 (Ref 1, p.1-62).

The comparison between the recommended cutting speeds (Tables 3.13 and 3.14) shows that ceramic and cermet tools can run at the cutting speeds twice as high as those for coated carbide tools (hardness range of 125–275 HB). Cermet tools can run at the cutting speeds 40% higher at

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Table 3.14. AISI 1030 to 1039, 1040 to 1046, 1050 to 1055 (16 grades total)

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Ceramic and cermet tool materials
125–175	0.300	0.015	1100	CPA
	0.150	0.010	1300	CPA
	0.040	0.005	1900	CPA
175–225	0.300	0.015	900	HPC
	0.150	0.010	1200	CPA
	0.040	0.005	1700	CPA
225–275	0.300	0.015	700	HPC
	0.150	0.010	1000	HPC
	0.040	0.005	1500	HPC
275–325	0.300	0.015	500	HPC
	0.150	0.010	800	HPC
	0.040	0.005	1300	HPC
325–375	0.300	0.012	450	HPC
	0.150	0.008	700	HPC
	0.040	0.004	1200	HPC
375–425	0.300	0.012	350	HPC
	0.150	0.008	550	HPC
	0.040	0.004	1000	HPC

roughing, 80% higher at semiroughing, and 100% higher at finishing compared to the cutting speeds for coated carbide tools (hardness range of 275–425 HB).

3.2.5. High-carbon steels

These steels are used when the highest available strength and superior surface hardness are needed. High-carbon steels provide better wear resistance than other carbon steels (except high-manganese carbon steels). When properly heat-treated, high-carbon steels are highly wear resistant and offer long tool life.

Ductility of the high-carbon steels is lower than that of the low- and medium-carbon steels, but can be improved through thermal treatment. None of AISI 1055 to 1095 grades contain more than 0.90% manganese.

For machining data on AISI 1055 high-carbon grade when turning with coated carbide tools, refer to the preceding Table 3.13 for the medium-carbon steels.

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Typical roughing, semiroughing, and finishing parameters for the high-carbon steels when turning with coated carbides are shown in Table 3.15 (Ref 1, p.1-9).

Table 3.15. AISI 1060 to 1069, 1070 to 1078, 1080 to 1095 (14 grades total)

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Coated carbide classification, C-grade / ISO
175–225	0.300	0.020	400	C6 / P30
	0.150	0.015	500	C6 / P20
	0.040	0.007	750	C7 / P10
225–275	0.300	0.020	375	C6 / P30
	0.150	0.015	475	C6 / P20
	0.040	0.007	700	C7 / P10
275–325	0.300	0.020	350	C6 / P30
	0.150	0.015	450	C6 / P20
	0.040	0.007	675	C7 / P10
325–375	0.300	0.020	300	C6 / P30
	0.150	0.015	375	C6 / P20
	0.040	0.007	550	C7 / P10
375–425	0.300	0.020	225	C6 / P30
	0.150	0.015	275	C6 / P20
	0.040	0.007	425	C7 / P10

As can be seen from Table 3.15, the way in which the cutting speeds are changing, in relationship with the hardness of steel and the type of operations, are similar to that for low- and medium carbon steels.

For machining data on AISI 1055 high-carbon grade when turning with ceramic and cermet tools, refer to the preceding Table 3.14 for the medium-carbon steels.

Typical roughing, semiroughing, and finishing parameters for high-carbon steels when turning with ceramic and cermet tools are shown in Table 3.16 (Ref 1, p.1-63).

The comparison between the recommended cutting speeds (Tables 3.15 and 3.16) shows that ceramic tools can run at the cutting speeds twice as high as those for coated carbide tools (hardness range of 175–225 HB). Cermet tools can run at the cutting speeds 45–60% higher at roughing, 80–100% higher at semiroughing, and 100–135% higher at finishing compared to the cutting speeds for coated carbide tools (hardness range of 275–425 HB).

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Table 3.16. AISI 1060 to 1069, 1070 to 1078, 1080 to 1095 (14 grades total)

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Ceramic and cermet tool materials
175–225	0.300	0.015	800	CPA
	0.150	0.010	1100	CPA
	0.040	0.005	1700	CPA
225–275	0.300	0.015	600	HPC
	0.150	0.010	900	CPA
	0.040	0.005	1500	CPA
275–325	0.300	0.015	500	HPC
	0.150	0.010	800	HPC
	0.040	0.005	1300	HPC
325–375	0.300	0.012	450	HPC
	0.150	0.008	700	HPC
	0.040	0.004	1200	HPC
375–425	0.300	0.012	350	HPC
	0.150	0.008	550	HPC
	0.040	0.004	1000	HPC

3.2.6. High-manganese carbon steels

American Iron and Steel Institute designates these steels as AISI 15xx series containing a minimum of 1.0% manganese and a maximum of 1.65% manganese. Similar to AISI 10xx carbon steels, high-manganese steels are divided into three categories: low-, medium-, and high-carbon steels.

The low-carbon steels contain 0.10–0.29% carbon and are used for carburizing applications, which require greater case hardenability than carbon steels of 10xx series can provide.

The medium-carbon 15xx steels (0.30–0.35% carbon) are widely used for parts machined from bar stock. These steels are suitable with or without heat treatment depending on applications.

The high-carbon 15xx steels (0.36–0.71% carbon) are used for parts, which need higher wear resistance and greater strength than those provided by 10xx steels.

For machining data on AISI 1513, 1518, and 1522 low-carbon grades when turning with coated carbide tools, refer to the preceding Table 3.2 for the low-carbon AISI 10xx steels.

For machining data on AISI 1525, 1526, and 1527 low-carbon grades when turning with coated carbide tools, refer to the preceding Table 3.13 for the medium-carbon AISI 10xx grades.

Typical roughing, semiroughing, and finishing parameters for medium-carbon, high-manganese steels are shown in Table 3.17 (Ref 1, p.1-8).

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Table 3.17. AISI 1524, 1536, 1541, 1547, 1548, 1551, and 1552

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Coated carbide classification, C-grade / ISO
125–175	0.300	0.020	450	C6 / P30
	0.150	0.015	550	C6 / P20
	0.040	0.007	850	C7 / P10
175–225	0.300	0.020	400	C6 / P30
	0.150	0.015	500	C6 / P20
	0.040	0.007	750	C7 / P10
225–275	0.300	0.020	375	C6 / P30
	0.150	0.015	475	C6 / P20
	0.040	0.007	725	C7 / P10
275–325	0.300	0.020	350	C6 / P30
	0.150	0.015	450	C6 / P20
	0.040	0.007	675	C7 / P10
325–375	0.300	0.020	315	C6 / P30
	0.150	0.015	375	C6 / P20
	0.040	0.007	575	C7 / P10
375–425	0.300	0.020	250	C6 / P30
	0.150	0.015	300	C6 / P20
	0.040	0.007	475	C7 / P10

As can be seen from Table 3.17, the way in which the cutting speeds are changing, in relationship with the hardness of steel and the type of operations, are similar to that for low-, medium- and high-carbon steels.

For machining data on AISI 1561, 1566, and 1572 high-carbon grades when turning with coated carbide tools, refer to the preceding Table 3.15 for the high-carbon AISI 10xx grades.

For machining data on AISI 1513, 1518, and 1522 low-carbon grades when turning with ceramic and cermet tools, refer to the preceding Table 3.4 for the low-carbon AISI 10xx grades.

For machining data on AISI 1525, 1526, and 1527 low-carbon grades when turning with ceramic and cermet tools, refer to the preceding Table 3.14 for the medium-carbon AISI 10xx grades.

Typical roughing, semiroughing, and finishing parameters for high-manganese carbon steels when turning with ceramic and cermet cutting tools are shown in Table 3.18 (Ref 1, pp.1-62, 1-63).

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Table 3.18. AISI 1524, 1536, 1541, 1547, 1548, 1551, and 1552

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Ceramic and cermet tool materials
125–175	0.300	0.015	1050	CPA
	0.150	0.010	1250	CPA
	0.040	0.005	1800	CPA
175–225	0.300	0.015	850	HPC
	0.150	0.010	1150	CPA
	0.040	0.005	1700	CPA
225–275	0.300	0.015	650	HPC
	0.150	0.010	950	HPC
	0.040	0.005	1500	HPC
275–325	0.300	0.015	450	HPC
	0.150	0.010	750	HPC
	0.040	0.005	1300	HPC
325–375	0.300	0.012	450	HPC
	0.150	0.008	700	HPC
	0.040	0.004	1200	HPC
375–425	0.300	0.012	350	HPC
	0.150	0.008	550	HPC
	0.040	0.004	1000	HPC

The comparison between the recommended cutting speeds (Tables 3.17 and 3.18) shows that ceramic tools can run at the cutting speeds twice as high as those for coated carbide tools (hardness range of 125–275 HB). Cermet tools can run at the cutting speeds 29–43% higher at roughing, 67–87% higher at semiroughing, and 93–110% higher at finishing compared to the cutting speeds for coated carbide tools (hardness range of 275–425 HB).

For machining data on AISI 1561, 1566, and 1572 high-carbon grades when turning with ceramic and cermet cutting tools, refer to the preceding Table 3.16 for the high-carbon AISI 10xx grades.

Concluding Remarks on the Cutting Speeds for Carbon Steels

1. Carbon steels are divided into six categories: nonresulfurized low-, medium-, and high-carbon steels (AISI 10xx grades); free-machining resulfurized steels (AISI 11xx grades); free-machining resulfurized and rephosphorized steels (AISI 12xx grades) and nonresulfurized high-manganese steels (AISI 15xx grades).

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2. There are 18 tables providing the cutting speed data depending on the category of carbon steels, their hardness, type of the cutting tool materials, and the type of operation: roughing, semi-roughing, and finishing.

3. Typical Brinell hardness range varies with the category of carbon steels:

- (85–225) HB for low-carbon steels (AISI 10xx grades)
- (100–200) HB for free-machining steels (AISI 11xx grades, AISI 12xx unleaded grades)
- (100–250) HB for free-machining steels (AISI 12Lxx grades, containing lead)
- (125–425) HB for medium-carbon steels (AISI 10xx grades)
- (175–425) HB for high-carbon steels (AISI 10xx grades)
- (125–425) HB for high-manganese steels (AISI 15xx grades).

4. Roughing, semiroughing, and finishing operations are performed at the different cutting speeds, which depend on the cutting tool materials.

Turning of carbon steels with coated carbide tools:

- Semiroughing is performed at the cutting speeds 19 to 28% higher than those to perform roughing.
- Finishing is performed at the cutting speeds 47 to 58% higher than those to perform semi roughing.

Turning of carbon steels with ceramic and cermet tools

Semiroughing is performed at the cutting speeds higher than those to perform roughing:

- 17–38% for low-carbon steels (AISI 10xx grades, 85–225 HB)
- 20–27% for free-machining steels (AISI 11xx grades, 100–200 HB)
- 16–20% for free-machining steels (AISI 12xx and 12Lxx grades, 100–250 HB)
- 33–60% for medium-carbon steels (AISI 10xx grades, hardness range 175–425 HB)
- 38–60% for high-carbon steels (AISI 10xx grades, hardness range 175–425 HB)
- 35–67% for high-manganese steels (AISI 15xx grades, hardness range 175–425 HB)

Finishing is performed at the cutting speeds higher than those to perform semiroughing:

- 31–41% for low-carbon steels (AISI 10xx grades, 85–225 HB)
- 22–29% for free-machining steels (AISI 11xx grades, 100–200 HB)
- 18–22% for free-machining steels (AISI 12xx and 12Lxx grades, 100–250 HB)
- 42–50% for medium-carbon steels (AISI 10xx grades, hardness range 125–275 HB)
- 62–82% for medium-carbon steels (AISI 10xx grades, hardness range 275–425 HB)
- 54–67% for high-carbon steels (AISI 10xx grades, hardness range 175–325 HB)
- 71–82% for high-carbon steels (AISI 10xx grades, hardness range 325–425 HB)
- 44–58% for high-manganese steels (AISI 15xx grades, hardness range 125–275 HB)
- 71–82% for high-manganese steels (AISI 15xx grades, hardness range 275–425 HB)

3.3. Cutting speeds for alloy steels

Alloy steels are not as common as carbon steels, but when hardness, strength, and wear resistance of the machined parts are a necessity, alloy steels are used (Ref 35, p.68). There are twelve categories of alloy steels, which differ from each other by the content of the principal alloying elements (for details, see pp.28, 29). The cutting speed recommendations are based on carbon contents and, therefore, all categories of alloy steels are divided into three groups: low-carbon, medium-carbon, and high-carbon grades.

3.3.1. Low-carbon alloy steels

Low-carbon alloy steels are those, which contain 0.07–0.30% C. This group includes 30 grades of the following alloy steel categories (Ref 8, p.76):

- Nickel steels: AISI A2317 and A2515
- Molybdenum steels: AISI 4023, 4024, 4419, 4422, and 4427

Table 3.19. The above-mentioned grades of low-carbon alloy steels

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Coated carbide classification, C-grade / ISO
125–175	0.300	0.020	475	C6 / P30
	0.150	0.015	625	C6 / P20
	0.040	0.007	775	C7 / P10
175–225	0.300	0.020	450	C6 / P30
	0.150	0.015	575	C6 / P20
	0.040	0.007	725	C7 / P10
225–275	0.300	0.020	400	C6 / P30
	0.150	0.015	500	C6 / P20
	0.040	0.007	650	C7 / P10
275–325	0.300	0.020	350	C6 / P30
	0.150	0.015	450	C6 / P20
	0.040	0.007	575	C7 / P10
325–375	0.300	0.020	300	C6 / P30
	0.150	0.015	375	C6 / P20
	0.040	0.007	475	C7 / P10
375–425	0.300	0.020	225	C6 / P30
	0.150	0.015	300	C6 / P20
	0.040	0.007	375	C7 / P10

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- Chromium-molybdenum steels: AISI 4118
- Nickel-molybdenum steels: AISI 4615, 4620, 4815, 4817, and 4820
- Chromium steels: AISI 5117 and 5120
- Chromium-vanadium steels: AISI 6118
- Nickel-chromium-molybdenum steels: AISI 4320, 4718, 4720, 8615, 8617, 8620, 8622, 8625, 8627, 8720, 8822, E9310, 94B15, and 94B17

Typical roughing, semiroughing, and finishing parameters for these low-carbon alloy steels when turning with coated carbide tools are shown in Table 3.19 (Ref 1, pp.1-12, 1-13; Ref 8, p.90).

As can be seen from Table 3.19, the cutting speed increases from roughing to semiroughing and reaches its maximum at finishing operation. The workpiece with higher hardness is machined at lower cutting speeds.

Typical roughing, semiroughing, and finishing parameters for the low-carbon alloy steels when turning with ceramic and cermet cutting tools are shown in Table 3.20 (Ref 1, p.1-66).

Table 3.20. Cutting data for low-carbon alloy steels

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V_c), sfm	Ceramic and cermet tool materials
125–175	0.300	0.015	1100	CPA
	0.150	0.010	1300	CPA
	0.040	0.005	1900	CPA
175–225	0.300	0.015	900	HPC
	0.150	0.010	1200	CPA
	0.040	0.005	1700	CPA
225–275	0.300	0.015	800	HPC
	0.150	0.010	1000	HPC
	0.040	0.005	1500	HPC
275–325	0.300	0.015	600	HPC
	0.150	0.010	800	HPC
	0.040	0.005	1300	HPC
325–375	0.300	0.012	450	HPC
	0.150	0.008	700	HPC
	0.040	0.004	1200	HPC
375–425	0.300	0.012	350	HPC
	0.150	0.008	550	HPC
	0.040	0.004	1000	HPC

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The comparison between the recommended cutting speeds (Tables 3.19 and 3.20) shows that ceramic and cermet tools can run at the cutting speeds 2.0–2.4 times higher than those for coated carbide tools (hardness range of 125–275 HB). Cermet tools can run at the cutting speeds 50–71% higher at roughing, 78–87% higher at semiroughing, and 126–167% higher at finishing compared to the cutting speeds for coated carbide tools (hardness range of 275–425 HB).

3.3.2. Medium-carbon alloy steels, Group 1

Medium-carbon alloy steels in Group 1 are those which contain 0.23–0.41% C. This group includes 15 grades of the following alloy steel categories (Ref 8, p.76).

- Manganese steels: AISI 1330 and 1335
- Molybdenum steels: AISI 4027, 4028, and 4037
- Chromium-molybdenum steels: AISI 4130, 4135, and 4137
- Nickel-molybdenum steels: AISI 4626
- Chromium steels: AISI 5130, 5132, and 5135
- Nickel-chromium-molybdenum steels: AISI 8630, 8637, and 94B30.

Typical roughing, semiroughing, and finishing parameters for these medium-carbon alloy steels when turning with coated carbide tools are shown in Table 3.21 (Ref 1, p.1-13; Ref 8, p.81). Turning with coated carbide tools.

Table 3.21. Grades of medium-carbon alloy steels included in Group 1

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Coated carbide classification, C-grade / ISO
175–225	0.300	0.020	400	C6 / P30
	0.150	0.015	525	C6 / P20
	0.040	0.007	650	C7 / P10
225–275	0.300	0.020	375	C6 / P30
	0.150	0.015	450	C6 / P20
	0.040	0.007	600	C7 / P10
275–325	0.300	0.020	350	C6 / P30
	0.150	0.015	425	C6 / P20
	0.040	0.007	550	C7 / P10
325–375	0.300	0.020	300	C6 / P30
	0.150	0.015	350	C6 / P20
	0.040	0.007	500	C7 / P10
375–425	0.300	0.020	225	C6 / P30
	0.150	0.015	300	C6 / P20
	0.040	0.007	375	C7 / P10

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As can be seen from Table 3.21, the way in which the cutting speeds are changing, in relationship with the hardness of steel and the type of operations, are similar to that for the low-carbon alloy steels.

Typical roughing, semiroughing, and finishing parameters for the same steels when turning with ceramic and cermet tools are shown in Table 3.22 (Ref 1, p.1-66).

Table 3.22. Grades of medium-carbon alloy steels included in Group 1

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V_c), sfm	Ceramic and cermet tool materials
175–225	0.300	0.015	875	HPC
	0.150	0.010	1175	CPA
	0.040	0.005	1700	CPA
225–275	0.300	0.015	775	HPC
	0.150	0.010	975	HPC
	0.040	0.005	1500	HPC
275–325	0.300	0.015	575	HPC
	0.150	0.010	775	HPC
	0.040	0.005	1300	HPC
325–375	0.300	0.012	450	HPC
	0.150	0.008	700	HPC
	0.040	0.004	1200	HPC
375–425	0.300	0.012	350	HPC
	0.150	0.008	550	HPC
	0.040	0.004	1000	HPC

The comparison between the recommended cutting speeds (Tables 3.21 and 3.22) shows that ceramic and cermet tools can run at the cutting speeds 2.1–2.6 higher than those for coated carbide tools (hardness range of 175–275 HB). Cermet tools can run at the cutting speeds 50–64% higher at roughing, 82–100% higher at semiroughing, and 136–167% higher at finishing compared to the cutting speeds for coated carbide tools (hardness range of 275–425 HB).

When the hardness of these grades exceeds 425 HB, then only hot pressed cermet tools (HPC) are used. Machining parameters are shown in Table 3.23.

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Table 3.23 Grades of medium-carbon alloy steels, Group 1.
Turning with cermet cutting tools (Ref 1, p.1-67)

Hardness		Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm
HRC	HB*			
45–48	421–456	0.300	0.008	250
		0.150	0.006	450
		0.040	0.003	900
48–50	456–480	0.150	0.006	400
		0.040	0.003	700
50–52	480–512	0.150	0.006	350
		0.040	0.003	600
52–54	512–544	0.150	0.006	300
		0.040	0.003	500
54–56	544–577	0.150	0.006	250
		0.040	0.003	400

*Conversion from Rockwell hardness (HRC) into Brinell hardness (HB) was performed by the author who used his equations 1.16 through 1.19.

3.3.3. Medium-carbon alloy steels, Group 2

Medium-carbon alloy steels in Group 2 are those, which contain 0.37–0.51% C. This group includes 21 grades of the following alloy steel categories (Ref 8, p.76).

- Manganese steels: AISI 1340 and 1345
- Nickel-chromium steels: AISI 3140
- Molybdenum steels: AISI 4042 and 4047
- Chromium-molybdenum steels: AISI 4140, 4142, 4145, and 4147
- Chromium steels: AISI 50B40, 50B44, 5046, 50B46, and 5140
- Nickel-chromium-molybdenum steels: AISI 4340, 81B45, 8640, 8642, 8645, 86B45, and 8740.

Typical roughing, semiroughing, and finishing parameters for these medium-carbon alloy steels when turning with coated carbide tools are shown in Table 3.24 (Ref 1, pp.1-14, 1-15; Ref 8, p.86).

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Table 3.24. Grades of medium-carbon alloy steels included in Group 2

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Coated carbide classification, C-grade / ISO
175–225	0.300	0.020	400	C6 / P30
	0.150	0.015	525	C6 / P20
	0.040	0.007	650	C7 / P10
225–275	0.300	0.020	375	C6 / P30
	0.150	0.015	475	C6 / P20
	0.040	0.007	600	C7 / P10
275–325	0.300	0.020	350	C6 / P30
	0.150	0.015	450	C6 / P20
	0.040	0.007	575	C7 / P10
325–375	0.300	0.020	300	C6 / P30
	0.150	0.015	400	C6 / P20
	0.040	0.007	500	C7 / P10
375–425	0.300	0.020	250	C6 / P30
	0.150	0.015	300	C6 / P20
	0.040	0.007	400	C7 / P10

As can be seen from Tables 3.21 and 3.24 (turning with coated carbide tools), there is no difference in the cutting speeds for grades in Group 1 and Group 2 at the hardness range of 175–275 HB. Cutting speeds at roughing are 11% higher for grades in Group 2 at the hardness range of 375–425 HB. Cutting speeds at semiroughing are 6% and 14% higher for grades in Group 2 at the hardness range of 275–325 HB and 325–375 HB respectively. Cutting speeds at finishing are 5% and 7% higher for grades in Group 2 at the hardness range of 275–325 HB and 375–425 HB respectively.

Typical roughing, semiroughing, and finishing parameters for the same grades of medium-carbon alloy steels in Group 2 when turning with ceramic and cermet tools are shown in Table 3.25 (Ref 1, p.1-67).

The comparison between the recommended cutting speeds (Tables 3.24 and 3.25) shows that ceramic and cermet tools can run at the cutting speeds 2.1–2.6 times higher than those for coated carbide tools (hardness range of 175–275 HB). Cermet tools can run at the cutting speeds 40–57% higher at roughing, 72–83% higher at semiroughing, and 126–150% higher at finishing compared to the cutting speeds for coated carbide tools (hardness range of 275–425 HB).

When the hardness of these grades exceeds 425 HB, then only hot pressed cermet tools (HPC) are used. Machining parameters are shown in Table 3.26.

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Table 3.25. Grades of medium-carbon alloy steels included in Group 2

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Ceramic and cermet tool materials
175–225	0.300	0.015	850	HPC
	0.150	0.010	1150	CPA
	0.040	0.005	1700	CPA
225–275	0.300	0.015	750	HPC
	0.150	0.010	950	HPC
	0.040	0.005	1500	HPC
275–325	0.300	0.015	550	HPC
	0.150	0.010	775	HPC
	0.040	0.005	1300	HPC
325–375	0.300	0.012	450	HPC
	0.150	0.008	700	HPC
	0.040	0.004	1200	HPC
375–425	0.300	0.012	350	HPC
	0.150	0.008	550	HPC
	0.040	0.004	1000	HPC

Table 3.26. Grades of medium-carbon alloy steels, Group 2.
Turning with cermet cutting tools (Ref 1, pp.1-67, 1-68)

Hardness		Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm
HRC	HB*			
45–48	421–456	0.300	0.008	250
		0.150	0.006	450
		0.040	0.003	900
48–50	456–480	0.150	0.006	400
		0.040	0.003	700
50–52	480–512	0.150	0.006	350
		0.040	0.003	600
52–54	512–544	0.150	0.006	300
		0.040	0.003	500
54–56	544–577	0.150	0.006	250
		0.040	0.003	400

*Conversion from Rockwell hardness (HRC) into Brinell hardness (HB) was performed by the author who used his equations 1.16 through 1.19.

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As can be seen from Tables 3.22 and 3.25 (turning with ceramic and cermet tools), there is no difference in the cutting speeds for grades in Group 1 and Group 2 at the hardness range of 325–425 HB. Cutting speeds at roughing are 3–5% higher for grades in Group 1 at the hardness range of 175–325 HB. Cutting speeds at semiroughing are 2–3% higher for grades in Group 1 at the hardness range of 175–275 HB. Cutting speeds at finishing are the same for grades in both groups at the hardness range of 175–425 HB.

As can be seen from Tables 3.23 and 3.26 (turning with cermet cutting tools), there is no difference in the cutting speeds for grades in Group 1 and Group 2 at the entire hardness range of 45–56 HRC (equivalent to 421–577 HB).

3.3.4. High-carbon alloy steels, Group 1

High-carbon alloy steels in Group 1 are those which contain 0.47–0.65% C. This group includes 16 grades of the following alloy steel categories (Ref 8, p.76).

- Chromium-molybdenum steels: AISI 4150 and 4162
- Chromium steels: AISI 50B50, 5060, 50B60, 5150, 5155, 5160, and 51B60
- Chromium-vanadium steels: AISI 6150
- Nickel-chromium-molybdenum steels: AISI 8650, 86B50, 8655, and 8660
- Silicon-manganese steels: AISI 9255 and 9260

Table 3.27. Grades of high-carbon alloy steels included in Group 1

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Coated carbide classification, C-grade / ISO
175–225	0.300	0.020	400	C6 / P30
	0.150	0.015	500	C6 / P20
	0.040	0.007	650	C7 / P10
225–275	0.300	0.020	350	C6 / P30
	0.150	0.015	450	C6 / P20
	0.040	0.007	575	C7 / P10
275–325	0.300	0.020	325	C6 / P30
	0.150	0.015	425	C6 / P20
	0.040	0.007	550	C7 / P10
325–375	0.300	0.020	275	C6 / P30
	0.150	0.015	350	C6 / P20
	0.040	0.007	450	C7 / P10
375–425	0.300	0.020	225	C6 / P30
	0.150	0.015	275	C6 / P20
	0.040	0.007	350	C7 / P10

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Typical roughing, semiroughing, and finishing parameters for these high-carbon alloy steels when turning with coated carbide tools are shown in Table 3.27 (Ref 1, pp.1-15, 1-16; Ref 8, p.123).

As can be seen from Table 3.27, the way in which the cutting speeds are changing in relationship with the hardness of steel and the type of operations, are similar to that for the medium-carbon alloy steels.

Typical roughing, semiroughing, and finishing parameters for the same steels when turning with ceramic and cermet tools are shown in Table 3.28 (Ref 1, p.1-68).

Table 3.28. Grades of high-carbon alloy steels included in Group 1

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Ceramic and cermet tool materials
175–225	0.300	0.015	825	HPC
	0.150	0.010	1125	CPA
	0.040	0.005	1700	CPA
225–275	0.300	0.015	725	HPC
	0.150	0.010	925	HPC
	0.040	0.005	1500	HPC
275–325	0.300	0.015	525	HPC
	0.150	0.010	750	HPC
	0.040	0.005	1300	HPC
325–375	0.300	0.012	450	HPC
	0.150	0.008	700	HPC
	0.040	0.004	1200	HPC
375–425	0.300	0.012	350	HPC
	0.150	0.008	550	HPC
	0.040	0.004	1000	HPC

The comparison between the recommended cutting speeds (Tables 3.27 and 3.28) shows that ceramic and cermet tools can run at the cutting speeds 2.1–2.6 times higher than those for coated carbide tools (hardness range of 175–275 HB). Cermet tools can run at the cutting speeds 56–64% higher at roughing, 76–100% higher at semiroughing, and 136–186% higher at finishing compared to the cutting speeds for coated carbide tools (hardness range of 275–425 HB).

When the hardness of these grades exceeds 425 HB, then only hot pressed cermet tools (HPC) are used. Feed rates and the cutting speeds are shown in Table 3.29.

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Table 3.29. Grades of high-carbon alloy steels, Group 1.
Turning with cermet cutting tools (Ref 1, pp.1-68, 1-69)

Hardness		Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm
HRC	HB*			
45–48	421–456	0.300	0.008	250
		0.150	0.006	450
		0.040	0.003	900
48–50	456–480	0.150	0.006	400
		0.040	0.003	700
50–52	480–512	0.150	0.006	350
		0.040	0.003	600
52–54	512–544	0.150	0.006	300
		0.040	0.003	500
54–56	544–577	0.150	0.006	250
		0.040	0.003	400

*Conversion from Rockwell hardness (HRC) into Brinell hardness (HB) was performed by the author who used his equations 1.16 through 1.19

3.3.5. High-carbon alloy steels, Group 2

High-carbon alloy steels in Group 2 are those which contain 0.98–1.10% C. This group includes only three grades of chromium, electric-furnace alloy steels: AISI E50100, E5100, and E52100 (Ref 8, p.154).

Typical roughing, semiroughing, and finishing parameters for these high-carbon alloy steels when turning with coated carbide tools are shown in Table 3.30 (Ref 1, p.1-17; Ref 8, p.156).

As can be seen from Tables 3.27 and 3.30 (turning with coated carbide tools), there is no difference in the cutting speeds for grades in Group1 and Group 2 to perform roughing at the hardness range of 175–425 HB. The cutting speeds are the same for grades in Group 1 and Group 2 at the hardness range of 225–275 HB and at the hardness range of 325–375 HB. Cutting speeds at semiroughing are 6% higher for grades in Group 1 (hardness range is 275–325 HB) and 9% higher for grades in Group 2 (hardness range is 375–425 HB). Cutting speeds at finishing are 4% and 5% higher for grades in Group 1 at the hardness range of 175–225 HB and 275–325 HB respectively. However, the cutting speed at finishing is 7% higher for grades in Group 2 (hardness range is 375–425 HB).

Typical roughing, semiroughing, and finishing parameters for the same grades of high-carbon alloy steels in Group 2 when turning with ceramic and cermet tools are shown in Table 3.31 (Ref 1, p.1-69).

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Table 3.30. Grades of high-carbon alloy steels included in Group 2

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Coated carbide classification, C-grade / ISO
175–225	0.300	0.020	400	C6 / P30
	0.150	0.015	500	C6 / P20
	0.040	0.007	625	C7 / P10
225–275	0.300	0.020	350	C6 / P30
	0.150	0.015	450	C6 / P20
	0.040	0.007	575	C7 / P10
275–325	0.300	0.020	325	C6 / P30
	0.150	0.015	400	C6 / P20
	0.040	0.007	525	C7 / P10
325–375	0.300	0.020	275	C6 / P30
	0.150	0.015	350	C6 / P20
	0.040	0.007	450	C7 / P10
375–425	0.300	0.020	225	C6 / P30
	0.150	0.015	300	C6 / P20
	0.040	0.007	375	C7 / P10

The comparison between the recommended cutting speeds (Tables 3.30 and 3.31) shows that ceramic and cermet tools can run at the cutting speeds 2.0–2.7 times higher than those for coated carbide tools (hardness range of 175–275 HB). Cermet tools can run at the cutting speeds 54–64% higher at roughing, 75–100% higher at semiroughing, and 148–167% higher at finishing compared to the cutting speeds for coated carbide tools (hardness range of 275–425 HB).

When the hardness of these grades exceeds 425 HB, then only hot pressed cermet tools (HPC) are used. Machining parameters are shown in Table 3.32.

As can be seen from Tables 3.28 and 3.31 (turning with ceramic and cermet tools), there is no difference in the cutting speeds for grades in Group1 and Group 2 at the hardness range of 325–425 HB. Cutting speeds at roughing are 3–5% higher for grades in Group 1 at the hardness range of 175–325 HB. Cutting speeds at semiroughing are 2–7% higher for grades in Group 1 at the hardness range of 175–325 HB. Cutting speeds at finishing are the same for grades in both groups at the hardness range of 175–425 HB.

As can be seen from Tables 3.29 and 3.32 (turning with cermet cutting tools), there is no difference in the cutting speeds for grades in Group1 and Group 2 at the entire hardness range of 45–56 HRC (equivalent to 421–577 HB).

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Table 3.31. Grades of high-carbon alloy steels included in Group 2

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Ceramic and cermet tool materials
175–225	0.300	0.015	800	HPC
	0.150	0.010	1100	CPA
	0.040	0.005	1700	CPA
225–275	0.300	0.015	700	HPC
	0.150	0.010	900	HPC
	0.040	0.005	1500	HPC
275–325	0.300	0.015	500	HPC
	0.150	0.010	700	HPC
	0.040	0.005	1300	HPC
325–375	0.300	0.012	450	HPC
	0.150	0.008	700	HPC
	0.040	0.004	1200	HPC
375–425	0.300	0.012	350	HPC
	0.150	0.008	550	HPC
	0.040	0.004	1000	HPC

Table 3.32. Grades of high-carbon alloy steels, Group 2.
Turning with cermet cutting tools (Ref 1, pp.1-69, 1-70)

Hardness		Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm
HRC	HB*			
45–48	421–456	0.300	0.008	250
		0.150	0.006	450
		0.040	0.003	900
48–50	456–480	0.150	0.006	400
		0.040	0.003	700
50–52	480–512	0.150	0.006	350
		0.040	0.003	600
52–54	512–544	0.150	0.006	300
		0.040	0.003	500
54–56	544–577	0.150	0.006	250
		0.040	0.003	400

Concluding Remarks on the Cutting Speeds for Alloy Steels

1. Alloy steels are divided into five categories depending on the carbon content: low-carbon (0.07–0.30% C), medium-carbon Grp. 1 (0.23–0.41% C), medium-carbon Grp. 2 (0.37–0.51% C), high-carbon Grp. 1 (0.47–0.65% C), and high-carbon Grp. 2 (0.98–1.00% C).

2. There are 14 tables providing the cutting speed data depending on the category of alloy steels, their hardness, type of the cutting tool materials, and the type of operation: roughing, semi-roughing, and finishing.

3. Typical Brinell hardness range varies with the category of alloy steels:

- (125–425) HB for the low-carbon alloy steels
- (175–425) HB for the medium-carbon and high-carbon alloy steels.

Coated carbide, ceramic, and cermet cutting tools are suitable for turning of low-, medium-, and high-carbon alloy steels at the above-mentioned hardness range.

4. Cermet cutting tools are suitable for turning of low-, medium-, and high-carbon alloy steels hardened to (45–56) HRC, which is equivalent to Brinell hardness range of (421–577) HB.

5. The cutting speed increases from roughing to semiroughing and reaches its maximum at finishing operation. The workpiece with higher hardness is machined at lower cutting speeds.

6. Roughing, semiroughing, and finishing operations are performed at the different cutting speeds, which depend on the cutting tool materials.

Turning of alloy steels with coated carbide tools:

- Semiroughing is performed at cutting speeds 17–33% higher than those needed to perform roughing.
- Finishing is performed at cutting speeds 24–43% higher than those needed to perform semiroughing.

Turning of alloy steels with ceramic and cermet tools

- Semiroughing is performed at cutting speeds 18–57% higher than those needed to perform roughing.
- Finishing is performed at cutting speeds 42–86% higher than those needed to perform semi roughing.

3.4. Cutting speeds for stainless steels

When deciding the best way to turn stainless steels, users have a wide assortment of cutting tool geometries and cutting tool materials to choose from and an array of machining parameters they can apply. Making the right choices depends on the type of stainless steel that is being turned (Ref 33, p.72).

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Stainless steels are divided into five categories: austenitic, martensitic, ferritic, duplex (ferritic-austenitic), and precipitation-hardening (for details see p.52). The cutting speed recommendations are based on the category of stainless steels.

Based on the recommended cutting speeds, each category of stainless steel is divided into several groups: austenitic steels are divided into three groups; martensitic steels into four groups; ferritic steels into two groups; and precipitation-hardening steels are combined in one group.

3.4.1. Austenitic stainless steels, Group 1

Group 1 includes 15 grades of austenitic stainless steels. Among them 2 standard chromium-nickel-manganese grades: AISI types 201 and 202. There are 13 chromium-nickel grades including 12 standard grades: AISI types 301, 302, 304, 304L, S30430, 304N, 305, 308, 321, 347, 348, and 384 (Ref 8, p.245) and a nonstandard AISI type 304HN grade (Ref 8, p.280).

Typical roughing, semiroughing, and finishing parameters for these grades of austenitic stainless steels when turning with coated carbide tools are shown in Table 3.33 (Ref 1, p.1-25; Ref 8, p.249).

Table 3.33. Grades of austenitic stainless steels included in Group 1

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Coated carbide classification, C-grade / ISO
135–185	0.300	0.020	350	C2 / K10, M10
	0.150	0.015	450	C3 / K10, M10
	0.040	0.007	525	C3 / K01, M10
225–275	0.300	0.020	300	C2 / K10, M10
	0.150	0.015	400	C3 / K10, M10
	0.040	0.007	450	C3 / K01, M10

As can be seen from Table 3.33, the way in which the cutting speeds are changing, in relationship with the hardness of steel and the type of operations, are similar to that for carbon and alloy steels.

Typical roughing, semiroughing, and finishing parameters for the same grades when turning with ceramic and cermet tools are shown in Table 3.34 (Ref 1, p.1-75).

The comparison between the recommended cutting speeds (Tables 3.33 and 3.34) shows that ceramic (CPA) tools can run at cutting speeds 71% higher at roughing, 100% higher at semiroughing, and 167% higher at finishing than coated carbide tools (hardness range of 135–185 HB). Cermet (HPC) tools can run at cutting speeds 67% higher at roughing, 100% higher at semiroughing, and 167% higher at finishing than coated carbide tools (hardness range of 225–275 HB).

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Table 3.34. Grades of austenitic stainless steels included in Group 1

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Ceramic and cermet tool materials
135–185	0.300	0.015	600	CPA
	0.150	0.010	900	CPA
	0.040	0.005	1400	CPA
225–275	0.300	0.015	500	HPC
	0.150	0.010	800	HPC
	0.040	0.005	1200	HPC

3.4.2. Austenitic stainless steels, Group 2

Group 2 includes 15 grades of austenitic stainless steels, among which are seven standard chromium-nickel grades: AISI types 302B, 309, 309S, 310, 310S, 314, and 330; seven standard chromium-nickel-molybdenum grades: AISI types 316, 316L, 316F, 316N, 317, 317L, and 329 (Ref 8, p.245); and a nonstandard AISI type 309S(Cb) chromium-nickel grade, which contains 0.8% Co (Nb) and Ta combined (Ref 8, p.285).

Chromium-nickel grades in Group 2 are distinct from those grades in Group 1, mainly in chemical composition: AISI types 302B and 314 grades contain more silicon (3.0% vs. 1.0–1.5%); the other grades contain more chromium (20–30% vs. 18–20%) and nickel (14–37% vs. 6–19%).

Typical roughing, semiroughing, and finishing parameters for austenitic stainless steels in Group 2 when turning with coated carbide tools are shown in Table 3.35 (Ref 1, pp.1-25, 1-26; Ref 8, p.263).

Table 3.35. Grades of austenitic stainless steels included in Group 2

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Coated carbide classification, C-grade / ISO
135–185	0.300	0.020	325	C2 / K10, M10
	0.150	0.015	425	C3 / K10, M10
	0.040	0.007	500	C3 / K01, M10
225–275	0.300	0.020	275	C2 / K10, M10
	0.150	0.015	350	C3 / K10, M10
	0.040	0.007	425	C3 / K01, M10

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As can be seen from Table 3.35, the way in which the cutting speeds are changing in relationship with the hardness of steel and the type of operations, are similar to that for austenitic stainless steels in Group 1.

The comparison between the recommended cutting speeds for coated carbide tools (Tables 3.33 and 3.35) show that grades in Group 1 can be machined at the cutting speeds 8–9% higher at roughing, 6–14% higher at semiroughing, and 5–6% higher at finishing operations than grades in Group 2.

Typical roughing, semiroughing, and finishing parameters for grades in Group 2 when turning with ceramic and cermet tools are shown in Table 3.36 (Ref 1, p.1-75).

Table 3.36. Grades of austenitic stainless steels included in Group 2

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Ceramic and cermet tool materials
135–185	0.300	0.015	550	CPA
	0.150	0.010	850	CPA
	0.040	0.005	1400	CPA
225–275	0.300	0.015	450	HPC
	0.150	0.010	750	HPC
	0.040	0.005	1200	HPC

The comparison between the recommended cutting speeds (Tables 3.35 and 3.36) shows that ceramic (CPA) tools can run at the cutting speeds 69% higher at roughing, 100% higher at semiroughing, and 180% higher at finishing than coated carbide tools (hardness range of 135–185 HB). Cermet (HPC) tools can run at the cutting speeds 64% higher at roughing, 114% higher at semiroughing, and 182% higher at finishing than coated carbide tools (hardness range of 225–275 HB).

The comparison between the recommended cutting speeds for ceramic (CPA) and cermet (HPC) cutting tools (Tables 3.34 and 3.36) show that grades in Group 1 can be machined at the cutting speeds 9–11% higher at roughing and 6–7% higher at semiroughing operations than grades in Group 2. The cutting speeds at finishing operation are the same.

3.4.3. Austenitic stainless steels, Group 3

Group 3 includes two standard chromium-nickel grades (17–19% Cr) of stainless steels: AISI types 303Se (0.15% selenium), 303 (Ref 8, p.245), and a nonstandard AISI 303 MA containing 0.4–0.6% Mo and 0.6–1.0% Al (Ref 8, p.271). The machinability rating of these grades is 80–85% (based on AISI 1212 steel as 100% average machinability), which is better than that of all chromium-nickel grades.

Typical roughing, semiroughing, and finishing parameters for austenitic stainless steels in Group 3 when turning with coated carbide tools are shown in Table 3.37 (Ref 1, p.1-24; Ref 8, p.269).

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Table 3.37. Grades of austenitic stainless steels included in Group 3

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Coated carbide classification, C-grade / ISO
135–185	0.300	0.020	475	C2 / K10, M10
	0.150	0.015	600	C2 / K10, M10
	0.040	0.007	700	C2 / K10, M10
225–275	0.300	0.020	300	C2 / K10, M10
	0.150	0.015	525	C2 / K10, M10
	0.040	0.007	600	C2 / K10, M10

Typical roughing, semiroughing, and finishing parameters for grades in Group 3 when turning with ceramic and cermet tools are shown in Table 3.38 (Ref 1, pp.1-74, 1-75).

Table 3.38. Grades of austenitic stainless steels included in Group 3

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Ceramic and cermet tool materials
135–185	0.300	0.015	800	CPA
	0.150	0.010	1100	CPA
	0.040	0.005	1600	CPA
225–275	0.300	0.015	600	HPC
	0.150	0.010	900	HPC
	0.040	0.005	1400	HPC

Because the regularity in recommending the cutting speeds versus type of steels (carbon, alloy, and stainless), their hardness, type of operations (roughing, semiroughing, and finishing), and type of the cutting tools (coated carbides, ceramics, and cermets) was established (Tables 3.1 through 3.36), the author won't provide further comparisons between the recommended cutting speeds vs. the above-mentioned variables, to avoid redundancy. It is up to the readers of this book to make, by themselves, comparisons between the cutting speeds for other grades of stainless steels and tool steels using the same method described earlier.

3.4.4. Martensitic stainless steels, Group 1

Group 1 includes three standard chromium grades of stainless steels: AISI types 403, 410, 422 (Ref 8, p.245), and a nonstandard AISI type 410S (Ref 8, p.328). These grades are limited to 11.0–13.5% chromium.

Typical roughing, semiroughing, and finishing parameters for martensitic stainless steels in

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Group 1 when turning with coated carbide tools are shown in Table 3.39 (Ref 1, p.1-26; Ref 8, p.319).

Typical roughing, semiroughing, and finishing parameters for grades in Group 1 when turning with ceramic and cermet tools are shown in Table 3.40 (Ref 1, p.1-76).

Table 3.39. Grades of martensitic stainless steels included in Group 1

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Coated carbide classification, C-grade / ISO
135–175	0.300	0.020	500	C6 / M20, P20
	0.150	0.015	625	C6 / M10, P10
	0.040	0.007	800	C7 / M10, P10
175–225	0.300	0.020	450	C6 / M20, P20
	0.150	0.015	550	C6 / M10, P10
	0.040	0.007	850	C7 / M10, P10
275–325	0.300	0.020	375	C6 / M20, P20
	0.150	0.015	450	C6 / M10, P10
	0.040	0.007	700	C7 / M10, P10
375–425	0.300	0.020	250	C6 / M20, P20
	0.150	0.015	300	C6 / M10, P10
	0.040	0.007	475	C7 / M10, P10

Table 3.40. Grades of martensitic stainless steels included in Group 1

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Ceramic and cermet tool materials
135–175	0.300	0.015	1000	CPA
	0.150	0.010	1300	CPA
	0.040	0.005	1800	CPA
175–225	0.300	0.015	800	HPC
	0.150	0.010	1100	HPC
	0.040	0.005	1600	HPC
275–325	0.300	0.015	500	HPC
	0.150	0.010	700	HPC
	0.040	0.005	1200	HPC
375–425	0.300	0.012	250	HPC
	0.150	0.008	450	HPC
	0.040	0.004	900	HPC

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3.4.5. Martensitic stainless steels, Group 2

Group 2 includes two standard chromium-nickel grades of stainless steels: AISI types 414 and 431. These grades are limited to 1.25–2.50% nickel (Ref 8, p.245).

Typical roughing, semiroughing, and finishing parameters for martensitic stainless steels in Group 2 when turning with coated carbide tools are shown in Table 3.41 (Ref 1, pp.1-26, 1-27; Ref 8, p.334).

Table 3.41. Grades of martensitic stainless steels included in Group 2

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Coated carbide classification, C-grade / ISO
225–275	0.300	0.020	350	C6 / M20, P20
	0.150	0.015	450	C6 / M10, P10
	0.040	0.007	575	C7 / M10, P10
275–325	0.300	0.020	300	C6 / M20, P20
	0.150	0.015	350	C6 / M10, P10
	0.040	0.007	500	C7 / M10, P10
375–425	0.300	0.020	250	C6 / M20, P20
	0.150	0.015	300	C6 / M10, P10
	0.040	0.007	400	C7 / M10, P10

Typical roughing, semiroughing, and finishing parameters for grades in Group 2 when turning with cermet (HPC) cutting tools are shown in Table 3.42 (Ref 1, p.1-76).

Table 3.42. Grades of martensitic stainless steels included in Group 2

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Cermet cutting tool materials
225–275	0.300	0.015	700	HPC
	0.150	0.010	900	HPC
	0.040	0.005	1400	HPC
275–325	0.300	0.015	450	HPC
	0.150	0.010	650	HPC
	0.040	0.005	1150	HPC
375–425	0.300	0.012	250	HPC
	0.150	0.008	450	HPC
	0.040	0.004	900	HPC

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Table 3.43. Grades of martensitic stainless steels included in Group 3

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V_c), sfm	Coated carbide classification, C-grade / ISO
135–185	0.300	0.020	600	C6 / M20, P20
	0.150	0.015	775	C6 / M10, P10
	0.040	0.007	875	C7 / M10, P10
185–240	0.300	0.020	400	C6 / M20, P20
	0.150	0.015	675	C6 / M10, P10
	0.040	0.007	775	C7 / M10, P10
275–325	0.300	0.020	400	C6 / M20, P20
	0.150	0.015	525	C6 / M10, P10
	0.040	0.007	575	C7 / M10, P10
375–425	0.300	0.015	200	C6 / M20, P20
	0.150	0.010	250	C6 / M10, P10
	0.040	0.005	300	C7 / M10, P10

Table 3.44. Grades of martensitic stainless steels included in Group 3

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V_c), sfm	Ceramic and cermet tool materials
135–185	0.300	0.015	900	CPA
	0.150	0.010	1200	CPA
	0.040	0.005	1800	CPA
185–240	0.300	0.015	700	HPC
	0.150	0.010	1000	HPC
	0.040	0.005	1500	HPC
275–325	0.300	0.012	500	HPC
	0.150	0.008	800	HPC
	0.040	0.004	1200	HPC
375–425	0.300	0.012	350	HPC
	0.150	0.008	550	HPC
	0.040	0.004	1000	HPC

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3.4.6. Martensitic stainless steels, Group 3

Group 3 includes four standard chromium grades (12.0–14% Cr) of stainless steels: AISI types 416, 416Se, 420, 420F (Ref 8, p.245), and a nonstandard AISI type 420F(Se) containing 0.60% molybdenum and 0.15% selenium (Ref 8, p.346).

Typical roughing, semiroughing, and finishing parameters for martensitic stainless steels in Group 3 when turning with coated carbide tools are shown in Table 3.43 (Ref 1, p.1-25; Ref 8, p.342).

Typical roughing, semiroughing, and finishing parameters for grades in Group 3 when turning with ceramic and cermet tools are shown in Table 3.44 (Ref 1, p.1-75).

3.4.7. Martensitic stainless steels, Group 4

Group 4 includes five high-chromium (16–18% Cr), high-carbon (0.60–1.20% C) grades of stainless steels. Among them are three standard grades: AISI types 440A, 440B, and 440C (Ref 8, p.245). There are also two nonstandard grades: AISI type 440F(Se) and 440F (Ref 8, p.366). All grades contain 0.75% molybdenum. AISI type 440F(Se) grade contains 0.10% selenium.

Typical roughing, semiroughing, and finishing parameters for martensitic stainless steels in Group 4 when turning with coated carbide tools are shown in Table 3.45 (Ref 1, p.1-27; Ref 8, p.359).

Table 3.45. Grades of martensitic stainless steels included in Group 4

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Coated carbide classification, C-grade / ISO
225–275	0.300	0.020	325	C6 / M20, P20
	0.150	0.015	400	C6 / M10, P10
	0.040	0.007	525	C7 / M10, P10
275–325	0.300	0.020	250	C6 / M20, P20
	0.150	0.015	325	C6 / M10, P10
	0.040	0.007	400	C7 / M10, P10

Typical roughing, semiroughing, and finishing parameters for grades in Group 4 when turning with cermet (HPC) cutting tools are shown in Table 3.46 (Ref 1, p.1-76).

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Table 3.46. Grades of martensitic stainless steels included in Group 4

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Cermet cutting tool materials
225–275	0.300	0.015	650	HPC
	0.150	0.010	850	HPC
	0.040	0.005	1400	HPC
275–325	0.300	0.015	400	HPC
	0.150	0.010	600	HPC
	0.040	0.005	1150	HPC
375–425	0.300	0.012	250	HPC
	0.150	0.008	450	HPC
	0.040	0.004	900	HPC

When the hardness of these martensitic grades exceeds 425 HB, then only semiroughing and finishing operations are performed with hot pressed cermet (HPC) tools. Machining parameters are shown in Table 3.47.

Table 3.47. Grades of martensitic steels, Group 4
Turning with cermet cutting tools (Ref 1, p.1-77)

Hardness		Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm
HRC	HB*			
48–52	456–512	0.150	0.006	350
		0.040	0.003	650
52–54	512–544	0.150	0.006	300
		0.040	0.003	500
54–56	544–577	0.150	0.006	250
		0.040	0.003	400

*Conversion from Rockwell hardness (HRC) into Brinell hardness (HB) was performed by the author who used his equations 1.16 through 1.19.

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3.4.8. Ferritic stainless steels, Group 1

Group 1 includes 12 grades of ferritic stainless steels. There are 8 standard grades: AISI types 405, 409, 429, 430, 434, 436, 442, and 446 (Ref 8, p.245), and four nonstandard grades: AISI types 430Ti, S43035, 435, and 443 (Ref 8, pp.352, 353, 367).

Typical roughing, semiroughing, and finishing parameters for ferritic stainless steels in Gp. 1 when turning with coated carbide tools are shown in Table 3.48 (Ref 1, p.1-25; Ref 8, p.325).

Table 3.48. Grades of ferritic stainless steels included in Group 1

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Coated carbide classification, C-grade / ISO
135–185	0.300	0.020	525	C6 / P20, K20
	0.150	0.015	650	C6 / P10, K10
	0.040	0.007	850	C7 / P10, K10

Typical roughing, semiroughing, and finishing parameters for ferritic stainless steels in Gp. 1 are shown in Table 3.49 (Ref 1, p.1-75). Turning with ceramic (CPA) cutting tools.

Table 3.49. Grades of ferritic stainless steels included in Group 1

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Ceramic cutting tool materials
135–185	0.300	0.015	700	CPA
	0.150	0.010	1000	CPA
	0.040	0.005	1500	CPA

3.4.9. Ferritic stainless steels, Group 2

Group 2 includes AISI types 430F and 430F(Se) standard grades (Ref 8, p.245).

Typical roughing, semiroughing, and finishing parameters for ferritic stainless steels in Gp. 2 when turning with coated carbide tools are shown in Table 3.50 (Ref 1, p.1-24; Ref 8, p.350).

Table 3.50. Grades of ferritic stainless steels included in Group 2

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Coated carbide classification, C-grade / ISO
135–185	0.300	0.020	600	C6 / P20, K20
	0.150	0.015	775	C6 / P10, K10
	0.040	0.007	875	C7 / P10, K10

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Typical roughing, semiroughing, and finishing parameters for ferritic stainless grades in Group 2 when turning with ceramic (CPA) cutting tools are shown in Table 3.51 (Ref 1, p.1-74).

Table 3.51. Grades of ferritic stainless steels included in Group 2

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Ceramic cutting tool materials
135–185	0.300	0.015	1000	CPA
	0.150	0.010	1300	CPA
	0.040	0.005	1700	CPA

3.4.10. Precipitation-hardening stainless steels

Precipitation-hardening stainless steels include four standard grades: UNS No. S13800, S15500, S17400, S17700 (Ref 8, p.245), and six nonstandard grades: S14800, S15700, S35000, S35500, S45000, and S45500 (Ref 8, pp.382, 386, 388, 403, 424, 426).

Typical roughing, semiroughing, and finishing parameters for these precipitation-hardening stainless steels when turning with coated carbide tools are shown in Table 3.52 (Ref 1, p.1-28; Ref 8, p.379).

Table 3.52. Grades of precipitation-hardening stainless steels

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Coated carbide classification, C-grade / ISO
150–200	0.300	0.020	350	C6 / M20, P20
	0.150	0.015	450	C6 / M10, P10
	0.040	0.007	525	C7 / M10, P10
275–325	0.300	0.020	300	C6 / M20, P20
	0.150	0.015	400	C6 / M10, P10
	0.040	0.007	450	C7 / M10, P10

Typical roughing, semiroughing, and finishing parameters for the above-mentioned precipitation-hardening grades when turning with ceramic and cermet cutting tools are shown in Table 3.53 (Ref 1, p.1-77).

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Table 3.53. Grades of precipitation-hardening stainless steels

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Ceramic and cermet tool materials
150–200	0.300	0.015	700	HPC
	0.150	0.010	1000	CPA
	0.040	0.005	1500	CPA
275–325	0.300	0.015	400	HPC
	0.150	0.010	600	HPC
	0.040	0.005	1100	HPC
325–375	0.300	0.012	300	HPC
	0.150	0.008	500	HPC
	0.040	0.004	1000	HPC
375–440	0.300	0.012	250	HPC
	0.150	0.008	450	HPC
	0.040	0.004	900	HPC

Concluding Remarks on the Cutting Speeds for Stainless Steels

1. Stainless steels are divided into five categories: austenitic, martensitic, ferritic, duplex (ferritic-austenitic), and precipitation-hardening. Recommended cutting speeds depend on the category of stainless steels, hardness, and the type of the cutting tool materials (coated carbides, ceramics, and cermets).

2. Austenitic stainless steels are divided into three groups according to their chemical composition. Cutting speed data for each group are shown in two tables: one for turning with coated carbide tools, and the other for turning with ceramic and cermet tools. The total number of tables is six.

3. Martensitic stainless steels are divided into four groups according to their chemical composition. Cutting speed data for Groups 1, 2, and 3 are shown in two tables per group, similar to that for austenitic steels. Group 4 covers the cutting speed data in three tables: one for turning with coated carbide tools (the steel hardness is 225–325 HB), another for turning with ceramic and cermet tools (the steel hardness is 225–425 HB), and the last table for turning with cermet tools (the steel hardness is 456–577 HB). The total number of tables is nine.

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4. Ferritic stainless steels are divided into two groups based on the same principle as described in preceding paragraphs. The cutting speed data are shown in four tables.

5. The cutting speed data for precipitation-hardening stainless steels are based on the type of the cutting tools and presented in two tables.

3.5. Cutting speeds for tool steels

Tool steels are carbon, alloy, or high-speed steels, capable of being hardened and tempered. They are used as tools for cutting, forming, and shaping of work materials. Tool steels are also used as the work materials where resistance to wear, strength, toughness, and other properties are selected for optimum performance.

Tool steels are divided into seven categories: water-hardening, shock-resisting, cold-work, mold, low alloy special-purpose, hot-work, and high-speed steels (see p.71 for details). The cutting speed recommendations are based on the category of tool steels. Some categories of tool steels are divided into two or more groups, so the cutting speeds are provided for each group of that category.

3.5.1. Water-hardening tool steels

This category of tool steel includes three grades: W1, W2, and W5 (Ref 8, p.432). Typical roughing, semiroughing, and finishing parameters for these grades when turning with coated carbide tools are shown in Table 3.54 (Ref 1, p.1-22).

Table 3.54. Grades of water-hardening tool steels

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V_c), sfm	Coated carbide classification, C-grade / ISO
150–200	0.300	0.020	450	C6 / M30, P30
	0.150	0.015	550	C6 / M20, P20
	0.040	0.007	700	C7 / M10, P10

Typical roughing, semiroughing, and finishing parameters for the above-mentioned grades when turning with cermet tools are shown in Table 3.55 (Ref 1, p.1-73)

3.5.2. Shock-resisting tool steels

This category includes six grades: S1, S2, S4, S5, S6, and S7 (Ref 8, p.436). Typical roughing, semiroughing, and finishing parameters for these grades when turning with coated carbide tools are shown in Table 3.56 (Ref 1, p.1-22).

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Table 3.55. Grades of water-hardening tool steels

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Cermet cutting tool materials
150–200	0.300	0.015	750	HPC
	0.150	0.010	1000	HPC
	0.040	0.005	1600	HPC

Table 3.56. Grades of shock-resisting tool steels

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Coated carbide classification, C-grade / ISO
175–225	0.300	0.020	400	C6 / M30, P30
	0.150	0.015	525	C6 / M20, P20
	0.040	0.007	675	C7 / M10, P10

Typical roughing, semiroughing, and finishing parameters for the above-mentioned grades when turning with cermet and ceramic cutting tools are shown in Table 3.57 (Ref 1, p.1-73).

Table 3.57. Grades of shock-resisting tool steels

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Cermet and ceramic tool materials
175–225	0.300	0.015	675	HPC
	0.150	0.010	875	CPA
	0.040	0.005	1475	CPA

3.5.3. Cold-work tool steels

This category of tool steels includes three sub-categories: oil-hardening (O), air-hardening (A), and high-carbon, high-chromium (D) steels. Based on the cutting speed recommendations, cold-work tool steels are divided into two groups.

Group 1 includes 4 grades of oil-hardening steels: O1, O2, O6, O7; and 8 grades of air-hardening steels: A2, A3, A4, A5, A6, A8, A9, and A10 (Ref 8, pp.440, 445).

Typical roughing, semiroughing, and finishing parameters for these grades when turning with coated carbide tools are shown in Table 3.58 (Ref 1, p.1-22).

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Table 3.58. Grades of cold-work tool steels included in Group 1

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Coated carbide classification, C-grade / ISO
200–250	0.300	0.020	350	C6 / M30, P30
	0.150	0.015	450	C6 / M20, P20
	0.040	0.007	575	C7 / M10, P10

Typical roughing, semiroughing, and finishing parameters for the above-mentioned grades when turning with cermet and ceramic cutting tools are shown in Table 3.59 (Ref 1, p.1-73).

Table 3.59. Grades of cold-work tool steels included in Group 1

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Cermet and ceramic tool materials
200–250	0.300	0.015	650	HPC
	0.150	0.010	850	HPC
	0.040	0.005	1450	CPA

Group 2 includes A7 grade of air-hardening tool steel and five grades of high-carbon, high-chromium tool steels: D2, D3, D4, D5, and D7 (Ref 8, pp.445, 449).

Typical roughing, semiroughing, and finishing parameters for these grades when turning with coated carbide tools are shown in Table 3.60 (Ref 1, p.1-21).

Table 3.60. Grades of cold-work tool steels included in Group 2

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Coated carbide classification, C-grade / ISO
200–250	0.300	0.015	200	C6 / M30, P30
	0.150	0.010	275	C6 / M20, P20
	0.040	0.005	575	C7 / M10, P10

Typical roughing, semiroughing, and finishing parameters for the above-mentioned grades when turning with cermet tools are shown in Table 3.61 (Ref 1, p.1-72).

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Table 3.61. Grades of cold-work tool steels included in Group 2

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Cermet cutting tool materials
200–250	0.300	0.015	550	HPC
	0.150	0.010	750	HPC
	0.040	0.005	1300	HPC

3.5.4. Mold tool steels

This category of tool steels includes seven grades: P2, P3, P4, P5, P6, P20, and P21 (Ref 8, p.453). Based on the cutting speed recommendations, mold tool steels are divided into two groups.

Group 1 includes five grades of mold steels: P2, P3, P4, P5, and P6. Typical roughing, semi-roughing, and finishing parameters for these grades when turning with coated carbide tools are shown in Table 3.62 (Ref 1, p.1-22).

Table 3.62. Grades of mold tool steels included in Group 1

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Coated carbide classification, C-grade / ISO
100–150	0.300	0.020	475	C6 / M30, P30
	0.150	0.015	625	C6 / M20, P20
	0.040	0.007	775	C7 / M10, P10

Typical roughing, semiroughing, and finishing parameters for the above-mentioned grades when turning with ceramic cutting tools are shown in Table 3.63 (Ref 1, p.1-73).

Table 3.63. Grades of mold tool steels included in Group 1

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Ceramic cutting tool materials
100–150	0.300	0.015	800	CPA
	0.150	0.010	1100	CPA
	0.040	0.005	1650	CPA

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Group 2 includes two grades of mold steels: P20 and P21. Typical roughing, semiroughing, and finishing parameters for these grades when turning with coated carbide tools are shown in Table 3.64 (Ref 1, p.1-22).

Table 3.64. Grades of mold tool steels included in Group 2

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Coated carbide classification, C-grade / ISO
150–200	0.300	0.020	475	C6 / M30, P30
	0.150	0.015	600	C6 / M20, P20
	0.040	0.007	750	C7 / M10, P10

Typical roughing, semiroughing, and finishing parameters for the above-mentioned grades when turning with ceramic cutting tools are shown in Table 3.65 (Ref 1, p.1-73).

Table 3.65. Grades of mold tool steels included in Group 2

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Ceramic cutting tool materials
150–200	0.300	0.015	850	CPA
	0.150	0.010	1150	CPA
	0.040	0.005	1700	CPA

3.5.5. Low-alloy special-purpose tool steels

Currently, only L2 and L6 grades of this tool steel category are in use (for details see p.80). Typical roughing, semiroughing, and finishing parameters for these grades when turning with coated carbide tools are shown in Table 3.66 (Ref 1, p.1-22).

Table 3.66. Grades of low-alloy special-purpose tool steels

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Coated carbide classification, C-grade / ISO
150–200	0.300	0.020	400	C6 / M30, P30
	0.150	0.015	525	C6 / M20, P20
	0.040	0.007	700	C7 / M10, P10

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Typical roughing, semiroughing, and finishing parameters for the above-mentioned grades when turning with ceramic cutting tools are shown in Table 3.67 (Ref 1, p.1-73).

Table 3.67. Grades of low-alloy special-purpose tool steels

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Ceramic cutting tool materials
150–200	0.300	0.015	650	CPA
	0.150	0.010	850	CPA
	0.040	0.005	1450	CPA

3.5.6. Hot-work tool steels

This category of tool steels includes fifteen grades: H10, H11, H12, H13, H14, H19, H21, H22, H23, H24, H25, H26, H41, H42, and H43 (Ref 8, p.457). Based on the cutting speed recommendations, hot-work tool steels are divided into two groups.

Group 1 includes 6 grades of hot-work, chromium type of tool steels: H10, H11, H12, H13, H14, and H19. Typical roughing, semiroughing, and finishing parameters for these grades when turning with coated carbide tools are shown in Table 3.68 (Ref 1, p.1-20).

Table 3.68. Grades of chromium type tool steels included in Group 1

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Coated carbide classification, C-grade / ISO
150–200	0.300	0.020	350	C6 / M30, P30
	0.150	0.015	425	C6 / M20, P20
	0.040	0.007	550	C7 / M10, P10
200–250	0.300	0.020	300	C6 / M30, P30
	0.150	0.015	400	C6 / M20, P20
	0.040	0.007	525	C7 / M10, P10
325–375	0.150	0.015	200	C6 / M20, P20
	0.040	0.007	250	C7 / M10, P10

Typical roughing, semiroughing, and finishing parameters for the above-mentioned grades when turning with ceramic and cermet cutting tools are shown in Table 3.69 (Ref 1, p.1-72).

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Table 3.69. Grades of chromium type tool steels included in Group 1

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Ceramic and cermet tool materials
150–200	0.300	0.015	750	CPA
	0.150	0.010	1050	CPA
	0.040	0.005	1600	CPA
200–250	0.300	0.015	650	HPC
	0.150	0.010	850	HPC
	0.040	0.005	1450	CPA
325–375	0.300	0.012	450	HPC
	0.150	0.008	700	HPC
	0.040	0.004	1200	HPC

When the hardness of these chromium type tool steels exceeds 375 HB, then only semiroughing and finishing operations are performed with hot pressed cermet (HPC) tools. Machining parameters are shown in Table 3.70.

Table 3.70. Grades of chromium type tool steels included in Group 1
Turning with cermet cutting tools (Ref 1, p.1-72)

Hardness		Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm
HRC	HB*			
48–50	456 to 480	0.150	0.006	400
		0.040	0.003	700
50–52	480 to 512	0.150	0.006	350
		0.040	0.003	600
52–54	512 to 544	0.150	0.006	300
		0.040	0.003	500
54–56	544 to 577	0.150	0.006	250
		0.040	0.003	400

*Conversion from Rockwell hardness (HRC) into Brinell hardness (HB) was performed by the author who used his equations 1.16 through 1.19

Group 2 includes 6 grades of hot-work, tungsten type of tool steels: H21, H22, H23, H24, H25, H26; and 3 grades of hot-work, molybdenum type of tool steels: H41, H42, and H43. Typical roughing, semiroughing, and finishing parameters for these grades when turning with coated carbide tools are shown in Table 3.71 (Ref 1, p.1-21).

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Table 3.71. Grades of hot-work tool steels included in Group 2

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Coated carbide classification, C-grade / ISO
150–200	0.300	0.020	325	C6 / M30, P30
	0.150	0.015	425	C6 / M20, P20
	0.040	0.007	550	C7 / M10, P10
200–250	0.300	0.020	300	C6 / M30, P30
	0.150	0.015	400	C6 / M20, P20
	0.040	0.007	525	C7 / M10, P10

Typical roughing, semiroughing, and finishing parameters for the above-mentioned grades when turning with ceramic and cermet cutting tools are shown in Table 3.72 (Ref 1, p.1-72).

Table 3.72. Grades of hot-work tool steels included in Group 2

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Ceramic and cermet tool materials
150–200	0.300	0.015	725	CPA
	0.150	0.010	1025	CPA
	0.040	0.005	1575	CPA
200–250	0.300	0.015	625	HPC
	0.150	0.010	825	HPC
	0.040	0.005	1425	CPA

3.5.7. High-speed tool steels

This category of high-speed tool steels includes seven tungsten-base grades: T1, T2, T4, T5, T6, T8, T15, and eighteen molybdenum-base grades: M1, M2, M3-class 1, M3-class 2, M4, M6, M7, M10, M30, M33, M34, M36, M41, M42, M43, M44, M46, and M47 (Ref 8, pp.463, 465). Based on the cutting speed recommendations, high-speed tool steels are divided into three groups.

Group 1 includes three tungsten-base grades: T1, T2, and T6, and four molybdenum-base grades: M1, M2, M6, and M10. Typical roughing, semiroughing, and finishing parameters for these grades when turning with coated carbide tools are shown in Table 3.73 (Ref 1, p.1-20).

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Table 3.73. Grades of high-speed tool steels included in Group 1

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Coated carbide classification, C-grade / ISO
200–250	0.300	0.020	325	C6 / M30, P30
	0.150	0.015	425	C6 / M20, P20
	0.040	0.007	525	C7 / M10, P10

Typical roughing, semiroughing, and finishing parameters for the above-mentioned grades when turning with cermet tools are shown in Table 3.74 (Ref 1, p.1-71)

Table 3.74. Grades of high-speed tool steels included in Group 1

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Cermet cutting tool materials
200–250	0.300	0.015	700	HPC
	0.150	0.010	900	HPC
	0.040	0.005	1500	HPC

Group 2 includes 3 tungsten-base grades: T4, T5, and T8, and 13 molybdenum-base grades: M3-class 1, M4, M7, M30, M33, M34, M36, M41, M42, M43, M44, M46, and M47. Typical roughing, semiroughing, and finishing parameters for these grades when turning with coated carbide tools are shown in Table 3.75 (Ref 1, p.1-20).

Table 3.75. Grades of high-speed tool steels included in Group 2

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Coated carbide classification, C-grade / ISO
225–275	0.300	0.020	300	C6 / M30, P30
	0.150	0.015	400	C6 / M20, P20
	0.040	0.007	500	C6 / M10, P10

Typical roughing, semiroughing, and finishing parameters for the above-mentioned grades when turning with cermet tools are shown in Table 3.76 (Ref 1, p.1-71).

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Table 3.76. Grades of high-speed tool steels included in Group 2

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Cermet cutting tool materials
225–275	0.300	0.015	650	HPC
	0.150	0.010	850	HPC
	0.040	0.005	1400	HPC

Group 3 includes one tungsten-base grade T15 and one molybdenum-base grade M3-class 2. Typical roughing, semiroughing, and finishing parameters for these grades when turning with coated carbide tools are shown in Table 3.77 (Ref 1, p.1-20).

Table 3.77. Grades of high-speed tool steels included in Group 3

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Coated carbide classification, C-grade / ISO
225–275	0.300	0.020	225	C6 / M30, P30
	0.150	0.015	300	C6 / M20, P20
	0.040	0.007	325	C6 / M10, P10

Typical roughing, semiroughing, and finishing parameters for the above-mentioned grades when turning with cermet tools are shown in Table 3.78 (Ref 1, p.1-72).

Table 3.78. Grades of high-speed tool steels included in Group 3

Brinell hardness, HB	Depth of cut (d), in.	Feed rate (f), ipr	Cutting speed, (V _c), sfm	Cermet cutting tool materials
225–275	0.300	0.015	625	HPC
	0.150	0.010	825	HPC
	0.040	0.005	1375	HPC

Concluding Remarks on the Cutting Speeds for Tool Steels

1. Tool steels are divided into seven categories: water-hardening, shock-resisting, cold-work, mold, low-alloy special-purpose, hot-work, and high-speed steels. Recommended cutting speeds depend on the category of tool steels, hardness, and the type of the cutting tool materials (coated carbides, ceramics, and cermets).
2. Cutting speed data for water-hardening (type W), shock-resisting (type S), and low-alloy special-purpose (type L) tool steels are provided in two tables for each category. There are 6 tables with the cutting speed data for these categories.
3. Each category of cold-work (types O, A, and D) and mold (type P) tool steels are divided into two groups, and the cutting speed data are provided in two tables for each group. Thus, there are 8 tables with the cutting speed data for these categories.
4. Hot-work (type H) category is divided into two groups: there are 2 tables with the cutting speed data for turning with coated carbide tools and 3 tables with the cutting speed data for turning with ceramic and cermet cutting tool. There are 5 tables total.
5. High-speed (types T and M) category is divided into three groups: there are 2 tables in each group (one table contains the cutting speed data for turning with coated carbide tools, the other table contains the cutting speed data for turning with ceramic and cermet cutting tool). There are 6 tables total.
6. The recommended cutting speed data for tool steels are provided in 25 tables.

Chapter 4

Machining Power

Calculating the required power at selected machining parameters is an essential step in managing the productivity of cutting. The calculation is based on the metal removal rate and the Unit Power. This method has been known for decades and is still widely used today.

4.1. Metal removal rate

Metal removal rate (Q) is the volume of metal removed per unit of time and expressed through the cutting speed (V_c), depth of cut (d), and feed rate (f). The formula for calculating metal removal rate is:

$$Q = 12 V_c \times d \times f \text{ (in.}^3\text{/min)} \quad (4.1)$$

where **12** is a conversion factor (12 in. = 1 ft) needed for the cutting speed, which is measured in *ft / min (sfm)*. The measure *ft / min (sfm)* is to be converted into *in / min*, because the depth of cut is measured in *inches*, and feed rate is in *inches per revolution (ipr)*.

Metal removal rate indicates the productivity of cutting.

4.2. Unit Power and Power Constant

The Unit Power data are given in *Machining Data Handbook* (Ref 2) and the Power Constant data are published in *Machinery's Handbook* of the last three editions: *26th Edition* (Ref 36, pp.1049, 1052), *27th Edition* (Ref 37, pp.1085, 1086), and *28th Edition* (Ref 16, pp.1055, 1056). The Power Constant data published in these editions of Machinery's Handbooks are the same.

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4.2.1. Unit Power values published in Machining Data Handbook

Average Unit Power requirements for turning of steels with carbide tools at the feed rates from 0.005–0.020 ipr are shown in Table 4.1 (Ref 2, p.17-10).

Table 4.1. Hardness of work materials and the Unit Power⁽¹⁾ values, K

Work material	Hardness range		K , hp / in. ³ /min	
	Brinell, HB	Rockwell	Sharp tool	Dull tools
Carbon steels, alloy steels, and tool steels	85–200	(52–93 HRB) ⁽²⁾	1.1	1.4
	(327–371) ⁽³⁾	35–40 HRC	1.4	1.7
	(371–480)	40–50 HRC	1.5	1.9
	(480–560)	50–55 HRC	2.0	2.5
	(560–614)	55–58 HRC	3.4	4.2
Ferritic, austenitic, and martensitic stainless steels	135–275	(74 HRB–28 HRC) ⁽²⁾	1.3	1.6
	(286–421)	30–45 HRC	1.4	1.7
Precipitation- hardening stainless steels	150–450	(80 HRB–48 HRC) ⁽²⁾	1.4	1.7

⁽¹⁾ Power requirements at spindle drive motor, corrected for 80% spindle drive efficiency.

⁽²⁾ Rockwell hardness numbers (Ref 16, pp.508, 510) added to this column by the author for comparison with the Brinell hardness numbers.

⁽³⁾ Brinell hardness numbers in parentheses were converted from Rockwell-C hardness numbers by the author and added to this column for comparison with HRC numbers.

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4.2.2. Power Constants published in Machinery's Handbook

Power Constant values (K_P) for turning of steel using sharp cutting tools are shown in Table 4.2 (Ref 16, pp.1055, 1056).

Table 4.2. Hardness of work materials and Power Constants, K_P , hp / in.³/min

Work material	Brinell Hardness range	K_P	Work material	Brinell Hardness range	K_P
Low-carbon, Medium-carbon, and High-carbon steels	80–100	0.63	Low-carbon, Medium-carbon, and High-carbon steels	220–240	0.89
	100–120	0.66		240–260	0.92
	120–140	0.69		260–280	0.95
	140–160	0.74		280–300	1.00
	160–180	0.78		300–320	1.03
	180–200	0.82		320–340	1.06
	200–220	0.85		340–360	1.14
Free-machining carbon steels: AISI 1108, 1109, 1110, 1116, 1117, 1118, 1119, 1132	100–120	0.41	Free-machining carbon steels: AISI 1137, 1139, 1140, 1141, 1144, 1146, 1151	180–200	0.51
	120–140	0.42		200–220	0.55
	140–160	0.44		220–240	0.57
	160–180	0.48		240–260	0.62
	180–200	0.50		...	...
Alloy steels: AISI 4023, 4024, 4027, 4028, 4037, 4042, 4047, 4137, 4140, 4142, 4145, 4147, 4150, 4340, 4815, 4817, 4820, 5130, 5132, 5135, 5140, 5150, 6118, 6150, 8637, 8640, 8642, 8645, 8650, 8740	140–160	0.62	Alloy steels: AISI 4130, 4320, 4615, 4620, 4626, 5120, 8615, 8617, 8620, 8622, 8625, 8630, 8720	140–160	0.56
	160–180	0.65		160–180	0.59
	180–200	0.69		180–200	0.62
	200–220	0.72		200–220	0.65
	220–240	0.76		220–240	0.70
	240–260	0.80		240–260	0.74
	260–280	0.84		260–280	0.77
	280–300	0.87		280–300	0.80
	300–320	0.91		300–320	0.83
	320–340	0.96		320–340	0.89
	340–360	1.00		...	...
Alloy steels: AISI 1330, 1335, 1340, E52100	160–180	0.79	Tool steels	175–200	0.75
	180–200	0.83		200–250	0.88
	200–220	0.87		250–300	0.98
Stainless steels	150–175	0.60		300–350	1.20
	175–200	0.72		350–400	1.30
	200–250	0.88		...	...

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4.2.3. Comparison between Unit Power and Power Constant values

As can be seen, the Unit Power values (Table 4.1) and the Power Constant values (Table 4.2) are significantly different when applied to the same type of steel.

The main problem of the information in Table 4.1 is that carbon, alloy, and tool steels are combined together, and the hardness of these steels and stainless steels is ranging too wide. It means that a given Unit Power value belongs to several categories of steel at a very broad range of hardness. Therefore, such values cannot provide accurate calculations of the required machining power.

The author addressed this problem at various conferences and in the articles published by various trade magazines. In Reassessing power factors (Ref 38, p.43), the author uses the term “P value” (equivalent to the power constant) obtained from the lab tests. Type of steels, hardness, and the *P* values are shown in Table 4.3.

Table 4.3. *P* values (hp / in.³/min) for selected types and grades of steels

Workpiece			<i>P</i> value at machining conditions		
Material	Designation	Brinell hardness	Roughing	General purpose ⁽¹⁾	Finishing
Carbon steel	AISI 1018	141	0.66	0.62	0.70
	AISI 1045	195	0.70	0.72	0.74
Alloy steel	AISI 4140	194	0.74	0.73	0.79
	AISI 4340	214	0.72	0.73	0.76
	AISI 4140	258	0.77	0.79	0.85
	AISI 4142	277	0.77	0.75	0.84
	AISI 4340	485	1.00	1.05	1.31
Tool steel	AISI Type H11	205	0.73	0.76	0.78
Stainless steel	AISI Type 316L	147	0.73	0.73	0.81
	AISI Type 410	243	0.71	0.74	0.81
	17-4 PH ⁽²⁾	294	0.70	0.72	0.99

⁽¹⁾ General purpose machining is similar to semiroughing operation.

⁽²⁾ 17-4 PH is a precipitation-hardening steel, currently designated as AISI type 630 and UNS S17400.

Power Constants *K_P* (Table 4.2) and the *P* values (Table 4.3) for carbon and alloy steels are in the same range. Here are some examples:

1. Carbon steels, Brinell hardness range (120-140) HB, *K_P* = 0.69 (Table 4.2)
Carbon steel AISI 1018, 141 HB, *P* = 0.62 – 0.70 (Table 4.3)
2. Alloy steel AISI 4340, Brinell hardness range (200-220) HB, *K_P* = 0.72 (Table 4.2)

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Alloy steel AISI 4340, 214 HB, $P = 0.72 - 0.76$ (Table 4.3)

3. Alloy steel AISI 4140, Brinell hardness range (240-260) HB, $K_P = 0.80$ (Table 4.2)

Alloy steel AISI 4140, 258 HB, $P = 0.77 - 0.85$ (Table 4.3)

4. Alloy steel AISI 4142, Brinell hardness range (260-280) HB, $K_P = 0.84$ (Table 4.2)

Alloy steel AISI 4142, 277 HB, $P = 0.75 - 0.84$ (Table 4.3).

Unfortunately, Power Constants K_P for tool steels and stainless steels (Table 4.2) do not represent a concrete category or grade of these steels, as that for carbon and alloy steels. In spite of this disadvantage, Power Constants K_P for steels are the most accurate and currently should be used for calculating required machining power.

The author conducted a study (Ref 39, pp.68, 69), which revealed that the power constant values are decreasing when feed rate and/or depth of cut are increasing, while the cutting speed remains constant. An increase in cutting speed (at a constant depth of cut and feed rate) slightly decreases the power constant. On the other hand, the maximum power constant values are always at low depth of cuts and low feed rates. This phenomenon can be explained by the fact that the higher the depth of cut and feed rate, the greater the volume of material removed from the work-piece and, as a result, the cutting process becomes more efficient.

Because the feed rates affect the Power Constants, the latter should be adjusted by the Feed factors, which depend on the feed rates as shown in the following table.

4.3. Calculating required machining power

The traditional method of calculating machining power is based on the metal removal rate (Q) and the Unit Power (K , Table 4.1). Because the Unit Power is corrected for 80% spindle drive efficiency, the machining power is, actually, the required power, or the power at the motor (P_m)

$$P_m = Q \times K \text{ (hp)} \quad (4.2)$$

Substitution of Q value from formula (4.1) into formula (4.2), gives:

$$P_m = 12 V_C \times d \times f \times K \text{ (hp)} \quad (4.3)$$

A more accurate method of calculating machining power (P), recommended by the author, is based on the metal removal rate (Q), Power Constant (K_P , Table 4.2), and Feed factor (C , Table 4.4). The following formula should be used for the calculation:

$$P = Q \times K_P \times C \text{ (hp)} \quad (4.4)$$

Substitution of Q value from formula (4.1) into formula (4.4) gives:

$$P = 12 V_C \times d \times f \times K_P \times C \text{ (hp)} \quad (4.5)$$

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Table 4.4. Feed factors for Power Constants (Ref 16, p.1057)

Feed rate, ipr	Feed factor, C	Feed rate, ipr	Feed factor, C
0.001	1.60	0.014	0.97
0.002	1.40	0.015	0.96
0.003	1.30	0.016	0.94
0.004	1.25	0.018	0.92
0.005	1.19	0.020	0.90
0.006	1.15	0.022	0.88
0.007	1.11	0.025	0.86
0.008	1.08	0.028	0.84
0.009	1.06	0.030	0.83
0.010	1.04	0.032	0.82
0.011	1.02	0.035	0.80
0.012	1.00	0.040	0.78
0.013	0.98	0.060	0.72

Required machining power (P_m) is calculated by the formula:

$$P_m = P / E \text{ (hp)} \quad (4.6)$$

Where E is a machine tool efficiency factor, which depends on the type of drive; the efficiency factors are shown in Table 4.5.

Table 4.5. Machine tool efficiency factors

Type of drive	E, %
Direct drive (integral-motor spindle)	94–95
Direct belt drive	90
Back gear drive	75
Geared head drive	70–80
Oil-hydraulic drive	60–90

Examples of calculating the required machining power

Example 1

The following calculations are based on the real case, which took place during Advanced Productivity Exposition (WESTEC-98, Los Angeles, CA).

A visitor, the owner of a machine shop, wanted to buy a 15-hp lathe for the following application:

- Workpiece – AISI 4140 alloy steel, hardness of (200 – 220) HB
- Machining conditions:
 - Cutting speed, 550 sfm,
 - Depth of cut, 0.200 in.,
 - Feed rate, 0.012 ipr

He was not sure if a 15-hp lathe would be the right choice, and asked a salesman of a machine tool company for advice. The salesman suggested a 30-hp machine tool for this kind of job. The machine shop owner wanted a second opinion and addressed this dilemma to the author who performed the following calculations.

1. Metal removal rate is calculated by formula (4.1)

$$Q = 12 \times 550 \times 0.2 \times 0.012 = 15.84 \text{ in.}^3 / \text{min}$$

2. Required machining power is calculated by formula (4.3)

$$P_m = Q \times K = 15.84 \times 1.1 = 17.4 \text{ hp}$$

where

$$K = 1.1 \text{ (Unit Power, Table 4.1, sharp tool)}$$

Based on formula (4.3), the required machining power is 17.4 hp.

3. For comparison, machining power is calculated by formula (4.4)

$$P = Q \times K_p \times C = 15.84 \times 0.72 \times 1 = 11.4 \text{ hp}$$

where

$$K_p = 0.72 \text{ (Power Constant, Table 4.2, sharp tool), } C = 1.00 \text{ (Table 4.4)}$$

4. Required machining power is calculated by formula (4.6)

$$P_m = P / E = 11.4 / 90 \cdot 100 = 12.7 \text{ hp}$$

where

$$E = 90\% \text{ (Table 4.5, Oil-hydraulic drive, assuming a new lathe)}$$

Conclusion:

The owner of a machine shop bought a 15-hp lathe.

Chapter 4

If the Unit Power (K) is used, the required machining power is higher than that calculated through the Power Constant (K_p) by: $17.4 / 12.7 \times 100 = 37\%$.

Example 2

- Workpiece – AISI 4340 alloy steel, hardness 350 HB
 - Machining conditions (see Table 3.24, p.146)
 - Depth of cut, $d = 0.150$ in.
 - Feed rate, $f = 0.015$ ipr
 - Cutting speed, $V_c = 400$ sfm
 - Unit Power $K = 1.5$ (Table 4.1)
 - Power Constant $K_p = 1.0$ (Table 4.2, hardness range 340 – 360 HB)
 - Feed factor $C = 0.96$ (Table 4.4)
 - Machine tool efficiency factor $E = 80\%$
1. Required machining power using $K = 1.5$ (traditional method of calculation):
 $P_m = Q \times K = 12 \times 400 \cdot 0.15 \times 0.015 \times 1.5 = 16.2$ hp
 2. Required machining power using $K_p = 1.0$ (suggested method of calculation):
 $P_m = Q \times K_p \times C / E = 12 \times 400 \times 0.15 \times 0.015 \times 1 \times 0.96 / 0.8 = 13.5$ hp

Conclusion:

In this particular case, the required machining power calculated by the traditional method (using Unit Power) is 20% higher than that calculated through Power Constant (the method recommended by the author).

Concluding Remarks on Machining Power

1. Calculating machining power at selected machining parameters is an essential step in managing the productivity of cutting.
2. The currently-used method of the machining power calculation is based on the metal removal rate and the Unit Power. This method of calculation is inaccurate because the Unit Power values (K) are not properly defined.
3. The method of calculating machining power suggested by the author is based on the metal removal rate, the Power Constant, and the Feed factor.
4. The Power Constant values (K_p) should be adjusted by Feed factors (C) in relation with the feed rates shown in Table 4.4.

5. Machine tool efficiency factors (Table 4.5) should be used when calculating required machining power. Because the machine tool efficiency factors (E) depend on the types of drive, the end users must identify them through technical characteristics of their machine tools.

Concluding Remarks

CUTTING DATA WHEN TURNING OF STEEL contains four chapters: Mechanical Properties of Steel, Cutting Tool Materials, Machining Recommendations, and Machining Power.

1. Mechanical Properties of Steel (Chapter 1) describes Brinell and Rockwell hardness, tensile strength, and machinability of steel.

1.1. The author developed 19 linear regression equations for hardness conversion: from Brinell (500-kgf load), Rockwell B-scale, and Rockwell C-scale into Brinell hardness at 3000-kgf load, which is one of the workpiece characteristics used when selecting machining parameters.

1.2. Classification of steels by commercial name or application is the most common system, which includes carbon steels, alloy steels, stainless steels, and tool steels described in this chapter.

1.3. The author studied the relationship between the tensile strength and Brinell hardness of these steels, applying statistical and linear regression analyses. As a result of this study, 174 engineering formulas were developed to calculate tensile strength versus Brinell hardness.

1.4. Hardness, tensile strength, and machinability of steels are the major mechanical properties described in this chapter. These properties are taken into consideration when selecting machining parameters.

2. Cutting Tool Materials (Chapter 2) described in this chapter are cemented carbides, cermets, ceramics, and tool steels. Although, tool steels are not used to fabricate indexable inserts for turning, the author described these steels because, chronologically, they were the first cutting tool materials in metalcutting.

2.1. Cemented carbides, especially CVD and PVD coated, are the most common cutting tool material for turning of steel. Classification systems for cemented carbides are based on the U.S. Industry code (C-grade) and ISO (International Organization for Standardization) code.

2.2. The C5 through C8 carbides are equivalent to P01 through P50 and the M10 through M40 grades. They are multcarbide materials, which contain various combinations of tungsten carbide, titanium carbide, tantalum carbide, and niobium carbide bonded with cobalt. These carbide grades are recommended for machining steels because they provide better crater resistance than other grades.

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2.3. Cermet cutting tools are capable of operating at higher cutting speeds than cemented carbides, and are suitable for finishing and semiroughing operations without coolant. Due to high resistance to plastic deformation and built-up edges, cermets produce excellent surface finishes.

2.4. Currently-used ceramics are based on aluminum oxide (white ceramic), aluminum oxide with titanium carbide (black ceramic), aluminum oxide reinforced with silicon carbide whiskers, silicon nitride, and sialon. Ceramics based on silicon nitride provide higher transverse rupture strength and fracture toughness than other types of ceramics. High hot hardness and chemical inertness make ceramic tools suitable for high-speed finishing operation.

2.5. PCBN (polycrystalline cubic boron nitride) cutting tools are most commonly used for machining various types of tool steels with the hardness ranging from 45–65 HRC.

3. Machining Recommendations (Chapter 3) include depth of cut, feed rate, and cutting speeds, which are major machining parameters in turning. Recommended machining parameters depend on the cutting tool materials and type of steel.

3.1. Depth of cut (d) and feed rate (f) are set according to the type of operations: roughing, semiroughing, or finishing, and to the type of cutting tool materials: cemented carbides or cermet-ceramics.

3.2. Turning with carbide tools is performed at $d = 0.300$ in. and $f = 0.020$ ipr to do roughing; at $d = 0.150$ in. and $f = 0.015$ ipr to do semiroughing; and at $d = 0.040$ in. and $f = 0.007$ ipr to do finishing. Sets of depth of cut and feed rate remain constant for all categories of steels (reduced feed rates are set for a few grades of martensitic stainless steels hardened to 375–425 HB, see Table 3.43, p.160).

3.3. Turning with cermet and ceramic tools is performed at the same depth of cuts as those when carbide tools are used. Feed rates are: 0.015 ipr at roughing, 0.010 ipr at semiroughing, and 0.005 ipr at finishing (steels at hardness range up to 300–350 HB). Feed rates are reduced to 0.012 ipr at roughing, 0.008 ipr at semiroughing, and 0.004 ipr at finishing (steels at the hardness range of 325–425 HB). Turning of quenched and tempered steels (hardness range of 45–56 HRC) is performed at 0.008 ipr at roughing, 0.006 ipr at semiroughing, and 0.003 ipr at finishing.

3.4. Cutting speeds depend on the category of steels, their hardness, operations, and type of the cutting tools. Recommended cutting speeds are shown in 78 tables.

3.5. Recommended cutting speeds for turning of all carbon steel categories (low-carbon, medium-carbon, high-carbon, free-machining, and high-manganese steels) are shown in Tables 3.1–3.18 (18 tables).

3.6. Recommended cutting speeds for turning of alloy steels (five groups) are shown in Tables 3.19–3.32 (14 tables).

3.7. Recommended cutting speeds for turning of stainless steels (ten groups) are shown in Tables 3.33–3.53 (21 tables).

3.8. Recommended cutting speeds for turning of tool steels (twelve groups) are shown in Tables 3.54–3.78 (25 tables).

Concluding Remarks

4. Machining Power (Chapter 4) describes two methods of power calculations: traditional method based on the Unit Power (Table 4.1) and the method based on the Power Constant (Table 4.2).

4.1. The disadvantage of the Unit Power values is that carbon, alloy, and tool steels are combined together, and the hardness of these steels and stainless steels ranges too wide. It means that a given Unit Power value belongs to several categories of steel at a broad range of hardness, so the calculated machining power is not accurate enough.

4.2. Power Constant values (Table 4.2) are defined for each category of steels at significantly narrower range of Brinell hardness (mostly, the increment is 20 HB); therefore, machining power is calculated more accurately.

4.3. Feed rate affects the efficiency of turning: the lower a feed rate is, the less efficient is turning. Therefore, Feed factors (Table 4.4) should be used to calculate machining power.

4.4. The most accurate method of calculating machining power for turning is based on Power Constant (K_P , Table 4.2) and Feed factor (C , Table 4.4). The author recommends this method of calculation to maximize the productivity of cutting.

APPENDIX 1. HARDNESS CONVERSION

Tables 1.1 - 1.5. Brinell hardness at 3000-kgf load converted from Brinell hardness at 500-kgf load

Tables 1.6 - 1.11. Brinell hardness at 3000-kgf load converted from Rockwell B hardness

Tables 1.12 - 1.19. Brinell hardness at 3000-kgf load converted from Rockwell C hardness

Tables 1.20 - 1.26. Vickers hardness at 10-kgf load converted from Rockwell A hardness

Appendix 1

Table 1.1. Conversion of Brinell hardness numbers at 500-kgf load (HB_5) into 3000-kgf load (HB_3)

Linear regression formula for calculating Brinell hardness at 3000-kgf load: $HB_C = 1.138 \times HB_5 - 1.052$

Brinell hardness numbers			Accuracy in calculating HB _C %	HB ₅ × HB ₃	(HB ₅) ²	(HB ₃) ²	Parameters of the regression line		Correlation coefficient
500-kgf load HB ₅	3000-kgf load						slope	intercept	
	actual HB ₃	calculated HB _C							
89	100	100	100	8900	7921	10000	1.138	-1.052	0.9962
90	101	101	100	9090	8100	10201			
91	103	102.5	<u>99.5</u>	9373	8281	10609			
92	104	104	<u>100</u>	9568	8464	10816			
94	106	106	100	9964	8836	11236			
95	107	107	100	10165	9025	11449			
96	108	108	100	10368	9216	11664			
98	110	110.5	99.6	10780	9604	12100			
99	112	112	100	11088	9801	12544			
844	951			89296	79248	100619			

The above formula provides 99.5 to 100% accuracy in calculating Brinell hardness at 3000-kgf load (HB_C)

The use of this formula is limited to Brinell hardness numbers from 89 to 100 at 500-kgf load (HB_5)

Table 1.2. Conversion of Brinell hardness numbers at 500-kgf load (HB_5) into 3000-kgf load (HB_3)

Linear regression formula for calculating Brinell hardness at 3000-kgf load: $HB_C = 1.224 \times HB_5 - 9.871$

Brinell hardness numbers			Accuracy in calculating HB _C %	HB ₅ × HB ₃	(HB ₅) ²	(HB ₃) ²	Parameters of the regression line		Correlation coefficient
500-kgf load HB ₅	actual HB ₃	calculated HB _C					slope	intercept	
101	114	114					100	11514	
102	116	115	99.1	11832	10404	13456			
104	117	117	100	12168	10816	13689			
106	119	119.9	99.3	12614	11236	14161			
107	121	121	100	12947	11449	14641			
109	123	124	100	13407	11881	15129			
110	125	125	100	13750	12100	15625			
112	127	127	100	14224	12544	16129			
114	130	130	100	14820	12996	16900			
116	132	132	100	15312	13456	17424			
118	135	135	100	15930	13924	18225			
120	137	137	100	16440	14400	18769			
1319	1496			164958	145407	187144			

The above formula provides 99.1 to 100% accuracy in calculating Brinell hardness at 3000-kgf load (HB_C)

The use of this formula is limited to Brinell hardness numbers from 101 to 120 at 500-kgf load (HB_5)

Appendix 1

Table 1.3. Conversion of Brinell hardness numbers at 500-kgf load (HB_5) into 3000-kgf load (HB_3)

Linear regression formula for calculating Brinell hardness at 3000-kgf load: $HB_C = 1.311 \times HB_5 - 21.047$

Brinell hardness numbers			Accuracy in calculating HB _C %	HB ₅ x HB ₃	(HB ₅) ²	(HB ₃) ²	Parameters of the regression line		Correlation coefficient
500-kgf load HB ₅	3000-kgf load								
	actual HB ₃	calculated HB _C					slope	intercept	
122	139	139	100	16958	14884	19321	1.311	-21.047	0.9988
124	141	141.5	99.6	17484	15376	19881			
126	144	144	100	18144	15876	20736			
128	147	147	100	18816	16384	21609			
130	150	149.4	99.6	19500	16900	22500			
133	153	153	100	20349	17689	23409			
135	156	156	100	21060	18225	24336			
137	159	159	100	21783	18769	25281			
140	162	162	100	22680	19600	26244			
1175	1351			176774	153703	203317			

The above formula provides 99.6 to 100% accuracy in calculating Brinell hardness at 3000-kgf load (HB_C)

The use of this formula is limited to Brinell hardness numbers from 121 to 140 at 500-kgf load (HB_5)

Table 1.4. Conversion of Brinell hardness numbers at 500-kgf load (HB_5) into 3000-kgf load (HB_3)

Linear regression formula for calculating Brinell hardness at 3000-kgf load: $HB_C = 1.369 \times HB_5 - 30.005$

Brinell hardness numbers			Accuracy in calculating HB _C %	HB ₅ x HB ₃	(HB ₅) ²	(HB ₃) ²	Parameters of the regression line		Correlation coefficient
500-kgf load HB ₅	3000-kgf load								
actual HB ₃	calculated HB _C	slope					intercept		
142	165	164.4	99.6	23430	20164	27225	1.369	-30.005	0.9967
145	169	169	100	24505	21025	28561			
148	172	172.6	99.6	25456	21904	29584			
151	176	176.7	99.6	26576	22801	30976			
154	180	180.8	<u>99.5</u>	27720	23716	32400			
157	185	185	<u>100</u>	29045	24649	34225			
160	190	189	99.5	30400	25600	36100			
1057	1237			187132	159859	219071			

The above formula provides 99.5 to 100% accuracy in calculating Brinell hardness at 3000-kgf load (HB_C)

The use of this formula is limited to Brinell hardness numbers from 141 to 160 at 500-kgf load (HB_5)

Table 1.5. Conversion of Brinell hardness numbers at 500-kgf load (HB_5) into 3000-kgf load (HB_3)Linear regression formula for calculating Brinell hardness at 3000-kgf load: $HB_C = 1.283 \times HB_5 - 14.218$

Brinell hardness numbers			Accuracy in calculating HB _C %	HB ₅ x HB ₃	(HB ₅) ²	(HB ₃) ²	Parameters of the regression line		Correlation coefficient
500-kgf load HB ₅	3000-kgf load								
	actual HB ₃	calculated HB _C							
163	195	195	100	31785	26569	38025	1.283	-14.218	0.9997
167	200	200	100	33400	27889	40000			
171	205	205	100	35055	29241	42025			
175	210	210	100	36750	30625	44100			
179	216	215.4	<u>99.7</u>	38664	32041	46656			
184	222	222	<u>100</u>	40848	33856	49284			
189	228	228	100	43092	35721	51984			
1228	1476			259594	215942	312074			

The above formula provides 99.7 to 100% accuracy in calculating Brinell hardness at 3000-kgf load (HB_C)The use of this formula is limited to Brinell hardness numbers from 161 to 189 at 500-kgf load (HB_5)

Table 1.6. Conversion of Rockwell B hardness into Brinell hardness (3000-kgf load)

Linear regression formula for calculating Brinell hardness: $HB_C = 2.136 \times HRB - 28.345$

Rockwell hardness, HRB	Brinell hardness		Accuracy in calculating HB_C %	HRB x HB	$(HRB)^2$	$(HB)^2$	Parameters of the regression line		Correlation coefficient
	actual HB	calculated HB_C					slope	intercept	
62.3	105	105	100	6541.5	3881.29	11025	2.136	-28.345	0.9990
65.4	111	111	100	7259.4	4277.16	12321			
66.7	114	114	100	7603.8	4448.89	12996			
67.6	116	116	100	7841.6	4569.76	13456			
69.8	121	121	100	8445.8	4872.04	14641			
331.8	567			37692	22049	64439			

The above formula provides 100% accuracy in calculating Brinell hardness

The use of this formula is limited to Rockwell B hardness range of 60.0 to 69.9 HRB

Table 1.7. Conversion of Rockwell B hardness into Brinell hardness (3000-kgf load)

Linear regression formula for calculating Brinell hardness: $HB_C = 2.579 \times HRB - 59.950$

Rockwell hardness, HRB	Brinell hardness		Accuracy in calculating HB_C %	HRB x HB	$(HRB)^2$	$(HB)^2$	Parameters of the regression line		Correlation coefficient
	actual HB	calculated HB_C					slope	intercept	
71.2	124	124	100	8828.8	5069.44	15376	2.579	-59.950	0.9991
72.0	126	126	100	9072.0	5184.00	15876			
74.2	131	131	100	9720.2	5505.64	17161			
75.0	133	133.5	99.6	9975.0	5625.00	17689			
76.4	137	137	100	10466.8	5836.96	18769			
78.7	143	143	100	11254.1	6193.69	20449			
79.7	146	146	100	11636.2	6352.09	21316			
527.2	940			70953	39767	126636			

The above formula provides 99.6 to 100% accuracy in calculating Brinell hardness

The use of this formula is limited to Rockwell B hardness range of 70.0 to 79.9 HRB

Table 1.8. Conversion of Rockwell B hardness into Brinell hardness (3000-kgf load)

Linear regression formula for calculating Brinell hardness: $HB_C = 3.303 \times HRB - 117.887$

Rockwell hardness, HRB	Brinell hardness		Accuracy in calculating HB_C %	HRB x HB	$(HRB)^2$	$(HB)^2$	Parameters of the regression line		Correlation coefficient
	actual HB	calculated HB_C					slope	intercept	
80.8	149	149	100	12039.2	6528.64	22201	3.303	-117.887	0.9997
81.7	152	152	100	12418.4	6674.89	23104			
82.9	156	156	100	12932.4	6872.41	24336			
83.9	159	159	100	13340.1	7039.21	25281			
85.0	163	163	100	13855.0	7225.00	26569			
414.3	779			64585.1	34340.15	121491			

The above formula provides 100% accuracy in calculating Brinell hardness

The use of this formula is limited to Rockwell B hardness range of 80.0 to 85.9 HRB

Table 1.9. Conversion of Rockwell B hardness into Brinell hardness (3000-kgf load)

Linear regression formula for calculating Brinell hardness: $HB_C = 4.031 \times HRB - 180.006$

Rockwell hardness, HRB	Brinell hardness		Accuracy in calculating HB_C %	HRB x HB	$(HRB)^2$	$(HB)^2$	Parameters of the regression line		Correlation coefficient
	actual HB	calculated HB_C					slope	intercept	
86.0	167	167	100	14362.0	7396.00	27889	4.031	-180.006	0.9971
87.1	171	171	100	14894.1	7586.41	29241			
88.0	174	174.7	<u>99.6</u>	15312.0	7744.00	30276			
89.0	179	179	<u>100</u>	15931.0	7921.00	32041			
89.5	181	181	100	16199.5	8010.25	32761			
439.6	872			76698.6	38657.66	152208			

The above formula provides 99.6 to 100% accuracy in calculating Brinell hardness

The use of this formula is limited to Rockwell B hardness range of 86.0 to 89.9 HRB

Table 1.10. Conversion of Rockwell B hardness into Brinell hardness (3000-kgf load)

Linear regression formula for calculating Brinell hardness: $HB_C = 5.289 \times HRB - 293.668$

Rockwell hardness, HRB	Brinell hardness		Accuracy in calculating HB_C %	HRB x HB	$(HRB)^2$	$(HB)^2$	Parameters of the regression line		Correlation coefficient
	actual HB	calculated HB_C					slope	intercept	
90.0	183	182.3	99.6	16470.0	8100.00	33489	5.289	-293.668	0.9986
90.9	187	187	100	16998.3	8262.81	34969			
91.9	192	192	100	17644.8	8445.61	36864			
92.8	197	197	100	18281.6	8611.84	38809			
93.7	201	201.9	99.5	18833.7	8779.69	40401			
94.6	207	207	100	19582.2	8949.16	42849			
95.5	212	211.4	99.7	20246.0	9120.25	44944			
649.4	1379			128057	60269	272325			

The above formula provides 99.5 to 100% accuracy in calculating Brinell hardness

The use of this formula is limited to Rockwell B hardness range of 90.0 to 95.9 HRB

Table 1.11. Converting Rockwell B hardness into Brinell hardness (3000-kgf load)

Linear regression formula for calculating Brinell hardness: $HB_C = 6.736 \times HRB - 432.340$

Rockwell hardness, HRB	Brinell hardness		Accuracy in calculating HB_C %	HRB x HB	$(HRB)^2$	$(HB)^2$	Parameters of the regression line		Correlation coefficient
	actual HB	calculated HB_C					slope	intercept	
96.4	217	217	100	20918.8	9292.96	47089	6.736	-432.340	0.9996
97.3	223	223	100	21697.9	9467.29	49729			
98.2	229	229	100	22487.8	9643.24	52441			
99.0	235	235	100	23265.0	9801.00	55225			
100.0	241	241	100	24100.0	10000.00	58081			
490.9	1145			112470	48204	262565			

The above formula provides 100% accuracy in calculating Brinell hardness

The use of this formula is limited to Rockwell B hardness range of 96.0 to 100 HRB

Appendix 1

Table 1.12. Conversion of Rockwell C hardness into Brinell hardness (3000-kgf applied load)

Linear regression formula for calculating Brinell hardness: $HB_C = 5.284 \times HRC + 120.491$

Rockwell hardness, HRC	Brinell hardness		Accuracy in calculating HB _C %	HRC x HB	(HRC) ²	(HB) ²	Parameters of the regression line		Correlation coefficient
	actual HB	calculated HB _C					slope	intercept	
20.5	229	229	100	4694.5	420.25	52441	5.284	120.491	0.9997
21.7	235	235	100	5099.5	470.89	55225			
22.8	241	241	100	5494.8	519.84	58081			
24.2	248	248	100	6001.6	585.64	61504			
25.4	255	255	100	6477.0	645.16	65025			
114.6	1208			27767.4	2641.78	292276			

The above formula provides 100% accuracy in calculating Brinell hardness

The use of this formula is limited to Rockwell C hardness range of 20.0 to 25.9 HRC

Table 1.13. Conversion of Rockwell C hardness into Brinell hardness (3000-kgf applied load)

Linear regression formula for calculating Brinell hardness: $HB_C = 6.888 \times HRC + 78.838$

Rockwell hardness, HRC	Brinell hardness		Accuracy in calculating HB _C %	HRC x HB	(HRC) ²	(HB) ²	Parameters of the regression line		Correlation coefficient
	actual HB	calculated HB _C					slope	intercept	
26.0	258	258	100	6708.0	676.00	66564	6.888	78.838	0.9999
26.6	262	262	100	6969.2	707.56	68644			
27.6	269	269	100	7424.4	761.76	72361			
28.8	277	277	100	7977.6	829.44	76729			
29.2	280	280	100	8176.0	852.64	78400			
29.8	284	284	100	8463.2	888.04	80656			
29.9	285	285	100	8521.5	894.01	81225			
197.9	1915			54239.9	5609.45	524579			

The above formula provides 100% accuracy in calculating Brinell hardness

The use of this formula is limited to Rockwell C hardness range of 26.0 to 29.9 HRC

Table 1.14. Conversion of Rockwell C hardness into Brinell hardness (3000-kgf load)

Linear regression formula for calculating Brinell hardness: $HB_C = 8.195 \times HRC + 39.932$

Rockwell hardness, HRC	Brinell hardness		Accuracy in calculating HB _C %	HRC x HB	(HRC) ²	(HB) ²	Parameters of the regression line		Correlation coefficient
	actual HB	calculated HB _C					slope	intercept	
30.0	286	286	100	8580.0	900.00	81796	8.195	39.932	0.99996
30.9	293	293	100	9053.7	954.81	85849			
33.1	311	311	100	10294.1	1095.61	96721			
34.3	321	321	100	11010.3	1176.49	103041			
35.5	331	331	100	11750.5	1260.25	109561			
163.8	1542			50688.6	5387.16	476968			

The above formula provides 100% accuracy in calculating Brinell hardness

The use of this formula is limited to Rockwell C hardness range of 30.0 to 35.9 HRC

Appendix 1

Table 1.15. Conversion of Rockwell C hardness into Brinell hardness (3000-kgf applied load)

Linear regression formula for calculating Brinell hardness: $HB_C = 8.718 \times HRC + 21.825$

Rockwell hardness, HRC	Brinell hardness		Accuracy in calculating HB_C %	HRC x HB	$(HRC)^2$	$(HB)^2$	Parameters of the regression line		Correlation coefficient
	actual HB	calculated HB_C					slope	intercept	
36.0	336	336	100	12096.0	1296.00	112896	8.718	21.825	0.9997
36.6	341	341	100	12480.6	1339.56	116281			
37.7	350	350	100	13195.0	1421.29	122500			
37.9	352	352	100	13340.8	1436.41	123904			
38.0	353	353	100	13414.0	1444.00	124609			
38.8	360	360	100	13968.0	1505.44	129600			
39.1	363	363	100	14193.3	1528.81	131769			
39.8	369	369	100	14686.2	1584.04	136161			
303.9	2824			107373.9	11555.55	997720			

The above formula provides 100% accuracy in calculating Brinell hardness

The use of this formula is limited to Rockwell C hardness range of 36.0 to 39.9 HRC

Table 1.16. Conversion of Rockwell C hardness into Brinell hardness (3000-kgf applied load)

Linear regression formula for calculating Brinell hardness: $HB_C = 10.057 \times HRC - 31.761$

Rockwell hardness, HRC	Brinell hardness		Accuracy in calculating HB_C %	HRC x HB	$(HRC)^2$	$(HB)^2$	Parameters of the regression line		Correlation coefficient
	actual HB	calculated HB_C					slope	intercept	
40.0	371	371	<u>100</u>	14840.0	1600.00	137641	10.057	-31.761	0.9994
40.4	375	375	100	15150.0	1632.16	140625			
41.8	388	388.6	99.8	16218.4	1747.24	150544			
43.1	401	402	99.8	17283.1	1857.61	160801			
44.5	415	416	99.8	18467.5	1980.25	172225			
45.7	429	427.8	<u>99.7</u>	19605.3	2088.49	184041			
255.5	2379			101564.3	10905.75	945877			

The above formula provides 99.7 to 100% accuracy in calculating Brinell hardness

The use of this formula is limited to Rockwell C hardness range of 40.0 to 45.9 HRC

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Table 1.17. Conversion of Rockwell C hardness into Brinell hardness (3000-kgf applied load)

Linear regression formula for calculating Brinell hardness: $HB_C = 12.642 \times HRC - 150.881$

Rockwell hardness, HRC	Brinell hardness		Accuracy in calculating HB_C %	HRC x HB	$(HRC)^2$	$(HB)^2$	Parameters of the regression line		Correlation coefficient
	actual HB	calculated HB_C					slope	intercept	
46.1	433	431.9	<u>99.7</u>	19961.3	2125.21	187489	12.642	-150.881	0.9989
46.9	442	442	<u>100</u>	20729.8	2199.61	195364			
47.0	443	443	100	20821.0	2209.00	196249			
47.7	452	452	100	21560.4	2275.29	204304			
48.0	455	456	99.8	21840.0	2304.00	207025			
48.5	461	462.3	99.7	22358.5	2352.25	212521			
49.0	469	469	100	22981.0	2401.00	219961			
49.6	477	476	99.8	23659.2	2460.16	227529			
49.8	479	479	100	23854.2	2480.04	229441			
432.6	4111			197765.4	20806.56	1879883			

The above formula provides 99.7 to 100% accuracy in calculating Brinell hardness

The use of this formula is limited to Rockwell C hardness range of 46.0 to 49.9 HRC

Table 1.18. Converting Rockwell C hardness into Brinell hardness (3000-kgf applied load)

Linear regression formula for calculating Brinell hardness: $HB_C = 15.979 \times HRC - 318.988$

Rockwell hardness, HRC	Brinell hardness:		Accuracy in calculating HB_C %	HRC x HB	$(HRC)^2$	$(HB)^2$	Parameters of the regression line		Correlation coefficient
	actual HB	calculated HB_C					slope	intercept	
50.0	481	480	<u>99.8</u>	24050.0	2500.00	231361	15.979	-318.988	0.9998
50.5	488	488	<u>100</u>	24644.0	2550.25	238144			
51.0	495	496	99.8	25245.0	2601.00	245025			
51.1	497	498	99.9	25396.7	2611.21	247009			
51.7	507	507	100	26211.9	2672.89	257049			
52.0	512	512	100	26624.0	2704.00	262144			
52.1	514	514	100	26779.4	2714.41	264196			
52.3	517	517	100	27039.1	2735.29	267289			
54.0	543	544	99.8	29322.0	2916.00	294849			
54.1	545	545.5	99.9	29484.5	2926.81	297025			
54.7	555	555	100	30358.5	2992.09	308025			
55.0	560	560	100	30800.0	3025.00	313600			
55.2	564	563.1	99.8	31132.8	3047.04	318096			
683.7	6778			357087.9	35995.99	3543812			

The above formula provides 99.8 to 100% accuracy in calculating Brinell hardness

The use of this formula is limited to Rockwell C hardness range of 50.0 to 55.9 HRC

Appendix 1

Table 1.19. Conversion of Rockwell C hardness into Brinell hardness (3000-kgf applied load)

Linear regression formula for calculating Brinell hardness: $HB_C = 18.694 \times HRC - 469.983$

Rockwell hardness, HRC	Brinell hardness		Accuracy in calculating HB_C %	HRC x HB	$(HRC)^2$	$(HB)^2$	Parameters of the regression line		Correlation coefficient
	actual HB	calculated HB_C					slope	intercept	
56.0	578	577	99.8	32368.0	3136.00	334084	18.694	-469.983	0.9993
56.3	582	582	100	32766.6	3169.69	338724			
56.8	591	591.8	99.9	33568.8	3226.24	349281			
57.0	595	595.6	99.9	33915.0	3249.00	354025			
57.3	601	601	100	34437.3	3283.29	361201			
57.8	611	611	100	35315.8	3340.84	373321			
58.0	615	614.3	99.9	35670.0	3364.00	378225			
58.3	620	620	100	36146.0	3398.89	384400			
58.7	627	627	100	36804.9	3445.69	393129			
516.2	5420			310992.4	29613.64	3266390			

The above formula provides 99.8 to 100% accuracy in calculating Brinell hardness

The use of this formula is limited to Rockwell C hardness range of 56.0 to 58.9 HRC

Table 1.20. Conversion of Rockwell A hardness into Vickers hardness (10-kgf applied load)

Linear regression formula for calculating Vickers hardness: $HV_C = 34 \times HRA - 2073$

Rockwell hardness, HRA	Vickers hardness		Accuracy in calculating HV_C %	HRA x HV	$(HRA)^2$	$(HV)^2$	Parameters of the linear regression line		Correlation coefficient
	actual HV	converted by the above formula, HV_C					slope	intercept	
Ref 9, p.112									
78.0	580	579	99.8	45240	6084.00	336400	34	-2073	0.9985
78.4	590	593	99.6	46256	6146.56	348100			
78.6	600	599	99.9	47160	6177.96	360000			
78.9	610	610	100	48129	6225.21	372100			
79.2	620	620	100	49104	6272.64	384400			
79.5	630	630	100	50085	6320.25	396900			
79.8	640	640	100	51072	6368.04	409600			
552.4	4270			337046	43594.66	2607500			

The above formula provides 99.6 to 100% accuracy to convert HRA into HV

The use of this formula is limited to Rockwell A hardness range of 78.0 to 79.9 HRA

Appendix 1

Table 1.21. Conversion of Rockwell A hardness into Vickers hardness (10-kgf applied load)

Linear regression formula for calculating Vickers hardness: $HV_C = 39 \times HRA - 2471$

Rockwell hardness, HRA	Vickers hardness		Accuracy in calculating HV_C %	HRA x HV	$(HRA)^2$	$(HV)^2$	Parameters of the linear regression line		Correlation coefficient
	actual HV	converted by the above formula, HV_C					slope	intercept	
Ref 9, p.112									
80.0	650	649	99.8	52000	6400.00	422500	39	-2471	0.9985
80.3	660	661	99.9	52998	6448.09	435600			
80.6	670	672	<u>99.6</u>	54002	6496.36	448900			
80.8	680	680	<u>100</u>	54944	6528.64	462400			
81.1	690	692	99.7	55959	6577.21	476100			
81.3	700	700	<u>100</u>	56910	6609.69	490000			
81.8	720	719	99.9	58896	6691.24	518400			
565.9	4770			385709	45751.23	3253900			

The above formula provides 99.6 to 100% accuracy to convert HRA into HV

The use of this formula is limited to Rockwell A hardness range of 80.0 to 81.9 HRA

Table 1.22. Conversion of Rockwell A hardness into Vickers hardness (10-kgf applied load)

Linear regression formula for calculating Vickers hardness: $HV_C = 50 \times HRA - 3370$

Rockwell hardness, HRA	Vickers hardness		Accuracy in calculating HV_C %	HRA x HV	$(HRA)^2$	$(HV)^2$	Parameters of the linear regression line		Correlation coefficient
	actual HV	converted by the above formula, HV_C					slope	intercept	
Ref 9, p.112									
82.2	740	740	100	60828	6756.84	547600	50	-3370	1.0000
82.6	760	760	100	62776	6822.76	577600			
83.0	780	780	100	64740	6889.00	608400			
83.4	800	800	100	66720	6955.56	640000			
83.8	820	820	100	68716	7022.44	672400			
415.0	3900			323780	34446.60	3046000			

The above formula provides 100% accuracy to convert HRA into HV

The use of this formula is limited to Rockwell A hardness range of 82.0 to 83.9 HRA

Table 1.23. Conversion of Rockwell A hardness into Vickers hardness (10-kgf applied load)

Linear regression formula for calculating Vickers hardness: $HV_C = 67 \times HRA - 4795$

Rockwell hardness, HRA	Vickers hardness		Accuracy in calculating HV_C %	HRA x HV	$(HRA)^2$	$(HV)^2$	Parameters of the linear regression line		Correlation coefficient
	actual HV	converted by the above formula, HV_C					slope	intercept	
Ref 9, p.112									
84.1	840	840	100	70644	7072.81	705600	67	-4795	1.0000
84.4	860	860	100	72584	7123.36	739600			
84.7	880	880	100	74536	7174.09	774400			
85.0	900	900	100	76500	7225.00	810000			
85.3	920	920	100	78476	7276.09	846400			
85.6	940	940	100	80464	7327.36	883600			
509.1	5340			453204	43198.71	4759600			

The above formula provides 100% accuracy to convert HRA into HV

The use of this formula is limited to Rockwell A hardness range of 84.0 to 85.9 HRA

Appendix 1

Table 1.24. Conversion of Rockwell A hardness into Vickers hardness (10-kgf applied load)

Linear regression formula for calculating Vickers hardness: $HV_C = 50 \times HRA - 3300$

Rockwell hardness, HRA	Vickers hardness		Accuracy in calculating HV_C %	HRA x HV	$(HRA)^2$	$(HV)^2$	Parameters of the linear regression line		Correlation coefficient
	actual HV	converted by the above formula, HV_C					slope	intercept	
Ref 20, p.19									
86.0	1000	1000	100	86000	7396.00	1000000	50	-3300	1.0000
86.5	1025	1025	100	88663	7482.25	1050625			
87.0	1050	1050	100	91350	7569.00	1102500			
259.5	3075			266013	22447.25	3153125			

The above formula provides 100% accuracy to convert HRA into HV

The use of this formula is limited to Rockwell A hardness range of 86.0 to 87.9 HRA

Table 1.25. Conversion of Rockwell A hardness into Vickers hardness (10-kgf applied load)

Linear regression formula for calculating Vickers hardness: $HV_C = 113 \times HRA - 8822$

Rockwell hardness, HRA	Vickers hardness		Accuracy in calculating HV_C %	HRA x HV	$(HRA)^2$	$(HV)^2$	Parameters of the linear regression line		Correlation coefficient
	actual HV	converted by the above formula, HV_C					slope	intercept	
Ref 20, p.19									
88.0	1130	1122	99.3	99440	7744.00	1276900	113	-8822	0.9988
88.5	1180	1179	99.9	104430	7832.25	1392400			
89.0	1225	1235	99.2	109025	7921.00	1500625			
89.5	1290	1292	99.9	115455	8010.25	1664100			
90.0	1340	1348	99.4	120600	8100.00	1795600			
90.5	1400	1405	99.7	126700	8190.25	1960000			
91.0	1465	1461	99.7	133315	8281.00	2146225			
91.5	1525	1518	99.5	139538	8372.25	2325625			
718.0	10555			948503	64451.00	14061475			

The above formula provides 99.2 to 99.9% accuracy to convert HRA into HV

The use of this formula is limited to Rockwell A hardness range of 88.0 to 91.9 HRA

Table 1.26. Conversion of Rockwell A hardness into Vickers hardness (10-kgf applied load)

Linear regression formula for calculating Vickers hardness: $HV_C = 176 \times HRA - 14614$

Rockwell hardness, HRA	Vickers hardness		Accuracy in calculating HV_C %	HRA x HV	$(HRA)^2$	$(HV)^2$	Parameters of the linear regression line		Correlation coefficient
	actual HV	converted by the above formula, HV_C					slope	intercept	
Ref 20, p.19									
92.0	1590	1578	99.2	146280	8464.00	2528100	176	-14614	0.9931
92.5	1660	1666	99.6	153550	8556.25	2755600			
93.0	1750	1754	99.8	162750	8649.00	3062500			
93.5	1820	1842	98.8	170170	8742.25	3312400			
94.0	1950	1930	99.0	183300	8836.00	3802500			
465.0	8770			816050	43247.50	15461100			

The above formula provides 98.8 to 99.8% accuracy to convert HRA into HV

The use of this formula is limited to Rockwell A hardness range of 92.0 to 94.0 HRA

APPENDIX 2. CARBON STEELS

TENSILE STRENGTH versus BRINELL HARDNESS

Tables 2.1A and 2.1B. AISI 1015 low-carbon steel

Tables 2.2A and 2.2B. AISI 1018 low-carbon steel

Tables 2.3A and 2.3B. AISI 1020 low-carbon steel

Tables 2.4A and 2.4B. AISI 1021 and 1022 low-carbon steels

Tables 2.5A and 2.5B. AISI 1025 low-carbon steel

Tables 2.6A and 2.6B. AISI 1030 medium-carbon steel

Tables 2.7A and 2.7B. AISI 1035 medium-carbon steel

Tables 2.8A and 2.8B. AISI 1040 medium-carbon steel

Tables 2.9A and 2.9B. AISI 1045 medium-carbon steel

Tables 2.10A and 2.10B. AISI 1050 medium-carbon steel

Tables 2.11A and 2.11B. AISI 1060 high-carbon steel

Tables 2.12A and 2.12B. AISI 1080 high-carbon steel

Tables 2.13A and 2.13B. AISI 1095 high-carbon steel

Tables 2.14A and 2.14B. AISI 1117 free-machining resulfurized steel

Tables 2.15A and 2.15B. AISI 1118 free-machining resulfurized steel

Tables 2.16A and 2.16B. AISI 1137 free-machining resulfurized steel

Tables 2.17A and 2.17B. AISI 1141 free-machining resulfurized steel

Tables 2.18A and 2.18B. AISI 1144 free-machining resulfurized steel

Tables 2.19A and 2.19B. AISI 1211, 1212, 1213, and 1215 free-machining resulfurized and rephosphorized steels

Tables 2.20A and 2.20B. AISI 1547 and 1548 high-manganese nonresulfurized steels

Appendix 2

Tensile strength of AISI 1015 low-carbon steel versus Brinell hardness (3000-kgf applied load)

Table 2.1A. Linear regression formula for calculating tensile strength: $\sigma = 468 \times \text{HB} + 4120$

Brinell hardness HB	Tensile strength, psi		Accuracy in calculating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, p.12									
101	50000	51388	97.3	5050000	10201	2.5E+09	468	4120	0.9967
111	56000	56068	<u>99.9</u>	6216000	12321	3.136E+09			
116	59250	58408	98.6	6873000	13456	3.511E+09			
116	60000	58408	97.3	6960000	13456	3.6E+09			
121	61500	60748	98.8	7441500	14641	3.782E+09			
121	62000	60748	98.0	7502000	14641	3.844E+09			
126	61000	63088	<u>96.7</u>	7686000	15876	3.721E+09			
126	63250	63088	99.7	7969500	15876	4.001E+09			
156	75500	77128	97.9	11778000	24336	5.7E+09			
217	106250	105676	99.5	23056250	47089	1.129E+10			
1,311	654,750			90532250	181893	4.508E+10			

Table 2.1B. Statistical formula for calculating tensile strength: $\sigma = 499 \times \text{HB}$

Brinell hardness HB	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, p.12		σ_a / HB	σ , psi	%	HB	σ , psi		
101	50000	495	50399	99.2	1,311	654,750	499	$\sigma = 499 \times \text{HB}$
111	56000	505	55389	98.9				
116	59250	511	57884	97.7				
116	60000	517	57884	<u>96.5</u>				
121	61500	508	60379	98.2				
121	62000	512	60379	97.4				
126	61000	484	62874	97.0				
126	63250	502	62874	<u>99.4</u>				
156	75500	484	77844	97.0				
217	106250	490	108283	98.1				

As can be seen from Tables 2.1A and 2.1B:

Linear regression formula provides 96.7 to 99.9% accuracy in calculating tensile strength

Statistical formula provides 96.5 to 99.4% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 100 to 220 HB

Appendix 2

Table 2.2A. Linear regression formula for calculating tensile strength: $\sigma = 493 \times \text{HB} + 398$

Brinell hardness HB	Tensile strength, psi		Accuracy in calculating σ %	HB $\times \sigma_a$	(HB) ²	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, p.13							493	398	0.9941
101	50000	50191	99.6	5050000	10201	2500000000			
111	55000	55121	99.8	6105000	12321	3025000000			
116	58000	57586	99.3	6728000	13456	3364000000			
121	60000	60051	99.9	7260000	14641	3600000000			
126	64000	62516	97.7	8064000	15876	4096000000			
131	65000	64981	100	8515000	17161	4225000000			
143	69000	70897	97.3	9867000	20449	4761000000			
143	70000	70897	98.7	10010000	20449	4900000000			
163	82000	80757	98.5	13366000	26569	6724000000			
1,155	573,000			74965000	151123	37195000000			

Table 2.2B. Statistical formula for calculating tensile strength: $\sigma = 496 \times \text{HB}$

Brinell hardness HB	Tensile strength σ _a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula	Accuracy in calculating σ	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ, psi		
Ref 8, p.13		σ _a / HB	σ, psi	%	HB	σ, psi		
101	50000	495	50096	99.8	1,155	573,000	496	σ = 496 x HB
111	55000	495	55056	99.9				
116	58000	500	57536	99.2				
121	60000	496	60016	100				
126	64000	508	62496	97.7				
131	65000	496	64976	99.96				
143	69000	483	70928	97.3				
143	70000	490	70928	98.7				
163	82000	503	80848	98.6				

As can be seen from Tables 2.2A and 2.2B:

Linear regression formula provides 97.3 to 99.97% accuracy in calculating tensile strength

Statistical formula provides 97.3 to 99.97% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 100 to 165 HB

Appendix 2

Tensile strength of AISI 1020 low-carbon steel versus Brinell hardness (3000-kgf applied load)

Table 2.3A. Linear regression formula for calculating tensile strength: $\sigma = 502 \times \text{HB} - 662$

Brinell hardness HB	Tensile strength, psi		Accuracy in calculating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, p.17							502	-662	0.9977
111	55000	55060	99.9	6105000	12321	3.025E+09			
111	57250	55060	96.2	6354750	12321	3.278E+09			
121	60000	60080	99.9	7260000	14641	3.6E+09			
121	61000	60080	98.5	7381000	14641	3.721E+09			
126	63500	62590	98.6	8001000	15876	4.032E+09			
131	64000	65100	98.3	8384000	17161	4.096E+09			
131	64500	65100	99.1	8449500	17161	4.16E+09			
137	68500	68112	99.4	9384500	18769	4.692E+09			
143	71250	71124	99.8	10188750	20449	5.077E+09			
156	75500	77650	97.2	11778000	24336	5.7E+09			
179	87000	89196	97.5	15573000	32041	7.569E+09			
255	129000	127348	98.7	32895000	65025	1.664E+10			
1,722	856,500			131754500	264742	6.559E+10			

Table 2.3B. Statistical formula for calculating tensile strength: $\sigma = 497 \times \text{HB}$

Brinell hardness HB	Tensile strength σ_a , psi	Strength-to-hardness ratio σ_a / HB	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, p.17								
111	55000	495	55167	99.7	1,722	856,500	497	$\sigma = 497 \times \text{HB}$
111	57250	516	55167	96.4				
121	60000	496	60137	99.8				
121	61000	504	60137	98.6				
126	63500	504	62622	98.6				
131	64000	489	65107	98.3				
131	64500	492	65107	99.1				
137	68500	500	68089	99.4				
143	71250	498	71071	99.7				
156	75500	484	77532	97.4				
179	87000	486	88963	97.8				
255	129000	506	126735	98.2				

As can be seen from Tables 2.3A and 2.3B

Linear regression formula provides 96.2 to 99.9% accuracy in calculating tensile strength

Statistical formula provides 96.4 to 99.8% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 110 to 255 HB

Appendix 2

Tensile strength of AISI 1021 and 1022 low-carbon steels versus Brinell hardness (3000-kgf applied load)

Table 2.4A. Linear regression formula for calculating tensile strength: $\sigma = 521 \times \text{HB} - 2962$

Brinell hardness HB	Tensile strength, psi		Accuracy in calculating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, pp.18, 19							521	-2962	0.9971
121	62000	60079	96.9	7502000	14641	3.844E+09			
131	67250	65289	97.1	8809750	17161	4.523E+09			
137	68750	68415	99.5	9418750	18769	4.727E+09			
137	69000	68415	99.2	9453000	18769	4.761E+09			
137	70250	68415	97.4	9624250	18769	4.935E+09			
143	70000	71541	97.8	10010000	20449	4.9E+09			
143	70500	71541	98.5	10081500	20449	4.97E+09			
149	73000	74667	97.8	10877000	22201	5.329E+09			
149	74000	74667	99.1	11026000	22201	5.476E+09			
163	80500	81961	98.2	13121500	26569	6.48E+09			
163	81500	81961	99.4	13284500	26569	6.642E+09			
163	82000	81961	100	13366000	26569	6.724E+09			
179	89000	90297	98.6	15931000	32041	7.921E+09			
262	135000	133540	98.9	35370000	68644	1.823E+10			
2,177	1,092,750			177875250	353801	8.946E+10			

Table 2.4B. Statistical formula for calculating tensile strength: $\sigma = 502 \times \text{HB}$

Brinell hardness HB	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, pp.18, 19		σ_a / HB	σ , psi	%	HB	σ , psi	ratio σ / HB	$\sigma = 502 \times \text{HB}$
121	62000	512	60742	98.0	2,177	1,092,750	502	
131	67250	513	65762	97.8				
137	68750	502	68774	100				
137	69000	504	68774	99.7				
137	70250	513	68774	97.9				
143	70000	490	71786	97.5				
143	70500	493	71786	98.2				
149	73000	490	74798	97.6				
149	74000	497	74798	98.9				
163	80500	494	81826	98.4				
163	81500	500	81826	99.6				
163	82000	503	81826	99.8				
179	89000	497	89858	99.0				
262	135000	515	131524	97.4				

As can be seen from Tables 2.4A and 2.4B:

Linear regression formula provides 96.9 to 100% accuracy in calculating tensile strength

Statistical formula provides 97.4 to 100% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 120 to 265 HB

Appendix 2

Tensile strength of AISI 1025 low-carbon steel versus Brinell hardness (3000-kgf applied load)

Table 2.5A. Linear regression formula for calculating tensile strength: $\sigma = 485 \times \text{HB} + 1462$

Brinell hardness HB	Tensile strength, psi		Accuracy in calculating σ %	HB x σ_a	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, p.21							485	1462	0.9942
101	50000	50447	99.1	5050000	10201	2.5E+09			
111	55000	55297	99.5	6105000	12321	3.025E+09			
116	58000	57722	99.5	6728000	13456	3.364E+09			
121	60000	60147	99.8	7260000	14641	3.6E+09			
126	64000	62572	<u>97.8</u>	8064000	15876	4.096E+09			
131	65000	64997	<u>100</u>	8515000	17161	4.225E+09			
143	70000	70817	98.8	10010000	20449	4.9E+09			
849	422,000			51732000	104105	2.571E+10			

Table 2.5B. Statistical formula for calculating tensile strength: $\sigma = 497 \times \text{HB}$

Brinell hardness HB	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ/HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, p.21		σ_a / HB	σ , psi	%	HB	σ , psi		
101	50000	495	50197	99.6	849	422,000	497	$\sigma = 497 \times \text{HB}$
111	55000	495	55167	99.7				
116	58000	500	57652	99.4				
121	60000	496	60137	<u>99.8</u>				
126	64000	508	62622	<u>97.8</u>				
131	65000	496	65107	<u>99.8</u>				
143	70000	490	71071	98.5				

As can be seen from Tables 2.5A and 2.5B:

Linear regression formula provides 97.8 to 100% accuracy in calculating tensile strength

Statistical formula provides 97.8 to 99.8% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 100 to 145 HB

Appendix 2

Tensile strength of AISI 1030 medium-carbon steel versus Brinell hardness (3000-kgf applied load)

Table 2.6A. Linear regression formula for calculating tensile strength: $\sigma = 471 \times \text{HB} + 4376$

Brinell hardness HB	Tensile strength, psi		Accuracy in calculating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, pp.22, 23							471	4376	0.9908
137	68000	68903	98.7	9316000	18769	4.624E+09			
149	74000	74555	99.3	11026000	22201	5.476E+09			
149	76000	74555	<u>98.1</u>	11324000	22201	5.776E+09			
156	78000	77852	<u>99.8</u>	12168000	24336	6.084E+09			
163	80000	81149	98.6	13040000	26569	6.4E+09			
163	81000	81149	99.8	13203000	26569	6.561E+09			
167	84000	83033	98.8	14028000	27889	7.056E+09			
170	84000	84446	99.5	14280000	28900	7.056E+09			
170	85000	84446	99.3	14450000	28900	7.225E+09			
170	86000	84446	98.2	14620000	28900	7.396E+09			
174	86000	86330	99.6	14964000	30276	7.396E+09			
179	88000	88685	99.2	15752000	32041	7.744E+09			
187	92000	92453	99.5	17204000	34969	8.464E+09			
2,134	1,062,000			175375000	352520	8.726E+10			

Table 2.6B. Statistical formula for calculating tensile strength: $\sigma = 498 \times \text{HB}$

Brinell hardness HB	Tensile strength σ_a , psi	Strength-to-hardness ratio σ_a / HB	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, pp.22, 23					2,134	1,062,000	498	$\sigma = 498 \times \text{HB}$
137	68000	496	68226	99.7				
149	74000	497	74202	99.7				
149	76000	510	74202	<u>97.6</u>				
156	78000	500	77688	99.6				
163	80000	491	81174	98.6				
163	81000	497	81174	<u>99.8</u>				
167	84000	503	83166	99.0				
170	84000	494	84660	99.2				
170	85000	500	84660	99.6				
170	86000	506	84660	98.4				
174	86000	494	86652	99.2				
179	88000	492	89142	98.7				
187	92000	492	93126	98.8				

As can be seen from Tables 2.6A and 2.6B:

Linear regression formula provides 98.1 to 99.8% accuracy in calculating tensile strength

Statistical formula provides 97.6 to 99.8% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 135 to 190 HB

Appendix 2

Tensile strength of AISI 1035 medium-carbon steel versus Brinell hardness (3000-kgf applied load)

Table 2.7A. Linear regression formula for calculating tensile strength: $\sigma = 502 \times \text{HB} - 634$

Brinell hardness HB	Tensile strength, psi		Accuracy in calcul- ating σ %	HB x σ_a	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
	Ref 8, p.23								
131	65000	65128	<u>99.8</u>	8515000	17161	4.225E+09	502	-634	0.9977
143	70000	71152	<u>98.4</u>	10010000	20449	4.9E+09			
143	72000	71152	98.8	10296000	20449	5.184E+09			
149	75000	74164	98.9	11175000	22201	5.625E+09			
163	80000	81192	98.5	13040000	26569	6.4E+09			
170	85000	84706	99.7	14450000	28900	7.225E+09			
179	90000	89224	99.1	16110000	32041	8.1E+09			
207	103000	103280	99.7	21321000	42849	1.061E+10			
1,285	640,000			104917000	210619	5.227E+10			

Table 2.7B. Statistical formula for calculating tensile strength: $\sigma = 498 \times \text{HB}$

Brinell hardness HB	Tensile strength σ _a , psi	Strength-to-hardness ratio σ _a / HB	Tensile strength calculated by the above formula σ, psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ/HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ, psi		
Ref 8, p.23					1,285	640,000	498	σ = 498 x HB
131	65000	496	65238	99.6				
143	70000	490	71214	98.3				
143	72000	503	71214	98.9				
149	75000	503	74202	98.9				
163	80000	491	81174	98.6				
170	85000	500	84660	99.6				
179	90000	503	89142	99.0				
207	103000	498	103086	99.9				

As can be seen from Tables 2.7A and 2.7B:

Linear regression formula provides 98.4 to 99.8% accuracy in calculating tensile strength

Statistical formula provides 98.3 to 99.9% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 130 to 210 HB

Appendix 2

Tensile strength of AISI 1040 medium-carbon steel versus Brinell hardness (3000-kgf applied load)

Table 2.8A. Linear regression formula for calculating tensile strength: $\sigma = 455 \times \text{HB} + 6954$

Brinell hardness HB	Tensile strength, psi		Accuracy in calculating σ %	HB x σ_a	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, pp.27, 28							455	6954	0.9936
143	70000	72019	<u>97.2</u>	10010000	20449	4.9E+09			
149	75000	74749	99.7	11175000	22201	5.625E+09			
149	75250	74749	99.3	11212250	22201	5.663E+09			
156	78750	77934	99.0	12285000	24336	6.202E+09			
163	80000	81119	98.6	13040000	26569	6.4E+09			
167	82500	82939	99.5	13777500	27889	6.806E+09			
167	84250	82939	98.4	14069750	27889	7.098E+09			
167	84500	82939	98.2	14111500	27889	7.14E+09			
170	82750	84304	98.2	14067500	28900	6.848E+09			
170	85000	84304	99.2	14450000	28900	7.225E+09			
170	85250	84304	98.9	14492500	28900	7.268E+09			
170	85500	84304	98.6	14535000	28900	7.31E+09			
174	86750	86124	99.3	15094500	30276	7.526E+09			
179	90000	88399	98.2	16110000	32041	8.1E+09			
183	88250	90219	97.8	16149750	33489	7.788E+09			
183	89000	90219	98.6	16287000	33489	7.921E+09			
187	91500	92039	99.4	17110500	34969	8.372E+09			
187	92250	92039	99.8	17250750	34969	8.51E+09			
192	94250	94314	<u>99.9</u>	18096000	36864	8.883E+09			
197	95000	96589	98.4	18715000	38809	9.025E+09			
197	96250	96589	99.6	18961250	38809	9.264E+09			
201	99000	98409	99.4	19899000	40401	9.801E+09			
207	100000	101139	98.9	20700000	42849	1E+10			
207	100500	101139	99.4	20803500	42849	1.01E+10			
207	101750	101139	99.4	21062250	42849	1.035E+10			
217	104750	105689	99.1	22730750	47089	1.097E+10			
217	107750	105689	98.1	23381750	47089	1.161E+10			
223	109000	108419	99.5	24307000	49729	1.188E+10			
5,099	2,514,750			463885000	941593	2.286E+11			

Statistical formula for calculating tensile strength is on the next page

Appendix 2

Tensile strength of AISI 1040 medium-carbon steel versus Brinell hardness (3000-kgf applied load)

Table 2.8B. Statistical formula for calculating tensile strength: $\sigma = 493 \times \text{HB}$

Brinell hardness HB	Tensile strength σ_a , psi	Strength-to-hardness ratio σ_a / HB	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, pp.27, 28					5,099	2,514,750	493	$\sigma = 493 \times \text{HB}$
143	70000	490	70499	99.3				
149	75000	503	73457	97.9				
149	75250	505	73457	97.6				
156	78750	505	76908	97.7				
163	80000	491	80359	99.6				
167	82500	494	82331	99.8				
167	84250	504	82331	97.7				
167	84500	506	82331	<u>97.4</u>				
170	82750	487	83810	98.7				
170	85000	500	83810	98.6				
170	85250	501	83810	98.3				
170	85500	503	83810	98.0				
174	86750	499	85782	98.9				
179	90000	503	88247	98.1				
183	88250	482	90219	97.8				
183	89000	486	90219	98.6				
187	91500	489	92191	99.3				
187	92250	493	92191	<u>99.9</u>				
192	94250	491	94656	99.6				
197	95000	482	97121	97.8				
197	96250	489	97121	99.1				
201	99000	493	99093	<u>99.9</u>				
207	100000	483	102051	98.0				
207	100500	486	102051	98.5				
207	101750	492	102051	99.7				
217	104750	483	106981	97.9				
217	107750	497	106981	99.3				
223	109000	489	109939	99.1				

Linear regression formula for calculating tensile strength is on previous page

As can be seen from Tables 2.8A and 2.8B:

Linear regression formula provides 97.2 to 99.9% accuracy in calculating tensile strength

Statistical formula provides 97.4 to 99.9% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 140 to 225 HB

Appendix 2

Tensile strength of AISI 1045 medium-carbon steel versus Brinell hardness (3000-kgf applied load)

Table 2.9A. Linear regression formula for calculating tensile strength: $\sigma = 567 \times \text{HB} - 11278$

Brinell hardness HB	Tensile strength, psi		Accuracy in calculating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, p.31									
163	80000	81143	98.6	1.E+07	26569	6.4E+09	567	-11278	0.9952
163	82000	81143	99.0	1.E+07	26569	6.72E+09			
170	85000	85112	99.9	1.E+07	28900	7.23E+09			
179	90000	90215	99.8	2.E+07	32041	8.1E+09			
179	91000	90215	99.1	2.E+07	32041	8.28E+09			
187	95000	94751	99.7	2.E+07	34969	9.03E+09			
197	100000	100421	99.6	2.E+07	38809	1E+10			
1,238	623,000			1.E+08	219898	5.58E+10			

Table 2.9B. Statistical formula for calculating tensile strength: $\sigma = 503 \times \text{HB}$

Brinell hardness HB	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ/HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, p.31		σ_a / HB	σ , psi	%				
163	80000	491	81989	97.6	1,238	623,000	503	$\sigma = 503 \times \text{HB}$
163	82000	503	81989	100				
170	85000	500	85510	99.4				
179	90000	503	90037	100				
179	91000	508	90037	98.9				
187	95000	508	94061	99.0				
197	100000	508	99091	99.1				

As can be seen from Tables 2.9A and 2.9B:

Linear regression formula provides 98.6 to 99.9% accuracy in calculating tensile strength

Statistical formula provides 97.6 to 100% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 160 to 200 HB

Appendix 2

Tensile strength of AISI 1050 medium-carbon steel versus Brinell hardness (3000-kgf applied load)

Table 2.10A. Linear regression formula for calculating tensile strength: $\sigma = 501 \times \text{HB} - 568$

Brinell hardness HB	Tensile strength, psi		Accuracy in calculating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, pp.32, 33							501	-568	0.9969
163	80000	81095	98.6	13040000	26569	6.4E+09			
170	85000	84602	99.5	14450000	28900	7.225E+09			
179	90000	89111	99.0	16110000	32041	8.1E+09			
187	92000	93119	98.8	17204000	34969	8.464E+09			
187	92200	93119	99.0	17241400	34969	8.501E+09			
187	95000	93119	<u>98.0</u>	17765000	34969	9.025E+09			
189	95000	94121	99.1	17955000	35721	9.025E+09			
197	96700	98129	98.5	19049900	38809	9.351E+09			
197	100000	98129	98.1	19700000	38809	1E+10			
201	100000	100133	99.9	20100000	40401	1E+10			
212	105000	105644	99.4	22260000	44944	1.103E+10			
212	106200	105644	99.5	22514400	44944	1.128E+10			
217	108500	108149	99.7	23544500	47089	1.177E+10			
217	109000	108149	99.2	23653000	47089	1.188E+10			
223	111500	111155	99.7	24864500	49729	1.243E+10			
223	112000	111155	99.2	24976000	49729	1.254E+10			
229	112200	114161	98.3	25693800	52441	1.259E+10			
229	112500	114161	98.5	25762500	52441	1.266E+10			
235	117200	117167	<u>100</u>	27542000	55225	1.374E+10			
241	119000	120173	99.0	28679000	58081	1.416E+10			
241	121000	120173	99.3	29161000	58081	1.464E+10			
248	122000	123680	98.6	30256000	61504	1.488E+10			
248	122500	123680	99.0	30380000	61504	1.501E+10			
248	122700	123680	99.2	30429600	61504	1.506E+10			
248	123500	123680	99.9	30628000	61504	1.525E+10			
255	129500	127187	98.2	33022500	65025	1.677E+10			
262	131200	130694	99.6	34374400	68644	1.721E+10			
262	132500	130694	98.6	34715000	68644	1.756E+10			
269	134000	134201	99.9	36046000	72361	1.796E+10			
6,376	3,177,900			711117500	1426640	3.545E+11			

Statistical formula for calculating tensile strength is on the next page

Appendix 2

Tensile strength of AISI 1050 medium-carbon steel versus Brinell hardness (3000-kgf applied load)

Table 2.10.B Statistical formula for calculating tensile strength: $\sigma = 498 \times \text{HB}$

Brinell hardness HB	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, pp.32, 33		σ_a / HB	σ , psi					
163	80000	491	81174	98.6	6,376	3,177,900	498	$\sigma = 498 \times \text{HB}$
170	85000	500	84660	99.6				
179	90000	503	89142	99.0				
187	92000	492	93126	98.8				
187	92200	493	93126	99.0				
187	95000	508	93126	<u>98.0</u>				
189	95000	503	94122	99.1				
197	96700	491	98106	98.6				
197	100000	508	98106	98.1				
201	100000	498	100098	99.9				
212	105000	495	105576	99.5				
212	106200	501	105576	99.4				
217	108500	500	108066	99.6				
217	109000	502	108066	99.1				
223	111500	500	111054	99.6				
223	112000	502	111054	99.2				
229	112200	490	114042	98.4				
229	112500	491	114042	98.6				
235	117200	499	117030	99.9				
241	119000	494	120018	99.2				
241	121000	502	120018	99.2				
248	122000	492	123504	98.8				
248	122500	494	123504	99.2				
248	122700	495	123504	99.3				
248	123500	498	123504	<u>100</u>				
255	129500	508	126990	98.1				
262	131200	501	130476	99.4				
262	132500	506	130476	98.5				
269	134000	498	133962	<u>100</u>				

Linear regression formula for calculating tensile strength is on previous page

As can be seen from Tables 2.10A and 2.10B:

Linear regression formula provides 98.0 to 100% accuracy in calculating tensile strength

Statistical formula provides 98.0 to 100% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 160 to 270 HB

Appendix 2

Tensile strength of AISI 1060 high-carbon steel versus Brinell hardness (3000-kgf applied load)

Table 2.11A. Linear regression formula for calculating tensile strength: $\sigma = 513 \times \text{HB} - 3597$

Brinell hardness HB	Tensile strength, psi		Accuracy in calcu- lating σ %	HB x σ_a	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, pp.35, 36							513	-3597	0.9956
179	91000	88230	<u>97.0</u>	16289000	32041	8.281E+09			
183	90000	90282	<u>99.7</u>	16470000	33489	8.1E+09			
223	108000	110802	97.5	24084000	49729	1.166E+10			
223	110000	110802	99.3	24530000	49729	1.21E+10			
229	112000	113880	98.3	25648000	52441	1.254E+10			
229	113000	113880	99.2	25877000	52441	1.277E+10			
241	118000	120036	98.3	28438000	58081	1.392E+10			
241	119000	120036	99.1	28679000	58081	1.416E+10			
248	124000	123627	<u>99.7</u>	30752000	61504	1.538E+10			
248	125000	123627	98.9	31000000	61504	1.563E+10			
255	128000	127218	99.4	32640000	65025	1.638E+10			
262	132000	130809	99.1	34584000	68644	1.742E+10			
262	133000	130809	98.4	34846000	68644	1.769E+10			
269	135000	134400	99.6	36315000	72361	1.823E+10			
269	136000	134400	98.8	36584000	72361	1.85E+10			
277	140000	138504	98.9	38780000	76729	1.96E+10			
285	143000	142608	<u>99.7</u>	40755000	81225	2.045E+10			
293	146000	146712	99.5	42778000	85849	2.132E+10			
302	149000	151329	98.5	44998000	91204	2.22E+10			
4,718	2,352,000			594047000	1191082	2.963E+11			

Statistical formula for calculating tensile strength is on the next page

Appendix 2

Tensile strength of AISI 1060 high-carbon steel versus Brinell hardness (3000-kgf applied load)

Table 2.11.B Statistical formula for calculating tensile strength: $\sigma = 499 \times \text{HB}$

Brinell hardness HB	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, pp.35, 36		σ_a / HB	σ , psi					
179	91000	508	89321	98.2	4,718	2,352,000	499	$\sigma = 499 \times \text{HB}$
183	90000	492	91317	98.6				
223	108000	484	111277	97.1				
223	110000	493	111277	98.9				
229	112000	489	114271	98.0				
229	113000	493	114271	98.9				
241	118000	490	120259	98.1				
241	119000	494	120259	99.0				
248	124000	500	123752	99.8				
248	125000	504	123752	99.0				
255	128000	502	127245	99.4				
262	132000	504	130738	99.0				
262	133000	508	130738	98.3				
269	135000	502	134231	99.4				
269	136000	506	134231	98.7				
277	140000	505	138223	98.7				
285	143000	502	142215	99.5				
293	146000	498	146207	99.9				
302	149000	493	150698	98.9				

Linear regression formula for calculating tensile strength is on previous page

As can be seen from Tables 2.11A and 2.11B:

Linear regression formula provides 97.0 to 99.7% accuracy in calculating tensile strength

Statistical formula provides 97.1 to 99.9% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 175 to 305 HB

Appendix 2

Tensile strength of AISI 1080 high-carbon steel versus Brinell hardness (3000-kgf applied load)

Table 2.12A. Linear regression formula for calculating tensile strength: $\sigma = 511 \times \text{HB} - 2109$

Brinell hardness HB	Tensile strength, psi		Accuracy in calculating σ %	HB x σ_a	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, pp.42, 43							511	-2109	0.9969
174	89000	86805	<u>97.5</u>	15486000	30276	7.921E+09			
192	98000	96003	98.0	18816000	36864	9.604E+09			
229	112000	114910	<u>97.5</u>	25648000	52441	1.254E+10			
269	134000	135350	99.0	36046000	72361	1.796E+10			
269	135000	135350	99.7	36315000	72361	1.823E+10			
277	140000	139438	99.6	38780000	76729	1.96E+10			
285	141000	143526	98.2	40185000	81225	1.988E+10			
293	146000	147614	98.9	42778000	85849	2.132E+10			
293	150000	147614	98.4	43950000	85849	2.25E+10			
302	150000	152213	98.5	45300000	91204	2.25E+10			
302	152000	152213	<u>99.9</u>	45904000	91204	2.31E+10			
311	157000	156812	<u>99.9</u>	48827000	96721	2.465E+10			
321	164000	161922	98.7	52644000	103041	2.69E+10			
331	166000	167032	99.4	54946000	109561	2.756E+10			
341	169000	172142	98.2	57629000	116281	2.856E+10			
341	171000	172142	99.3	58311000	116281	2.924E+10			
352	180000	177763	98.8	63360000	123904	3.24E+10			
352	182000	177763	97.7	64064000	123904	3.312E+10			
363	184000	183384	99.7	66792000	131769	3.386E+10			
5,597	2,820,000			8.558E+08	1697825	4.314E+11			

Statistical formula for calculating tensile strength is on the next page

Appendix 2

Tensile strength of AISI 1080 high-carbon steel versus Brinell hardness (3000-kgf applied load)

Table 2.12B. Statistical formula for calculating tensile strength: $\sigma = 504 \times \text{HB}$

Brinell hardness HB	Tensile strength σ_a , psi	Strength-to-hardness ratio σ_a / HB	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ/HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, pp.42, 43					5,597	2,820,000	504	$\sigma = 504 \times \text{HB}$
174	89000	511	87696	98.5				
192	98000	510	96768	98.7				
229	112000	489	115416	<u>97.0</u>				
269	134000	498	135576	98.8				
269	135000	502	135576	99.6				
277	140000	505	139608	99.7				
285	141000	495	143640	98.2				
293	146000	498	147672	98.9				
293	150000	512	147672	98.4				
302	150000	497	152208	98.5				
302	152000	503	152208	<u>99.9</u>				
311	157000	505	156744	99.8				
321	164000	511	161784	98.6				
331	166000	502	166824	99.5				
341	169000	496	171864	98.3				
341	171000	501	171864	99.5				
352	180000	511	177408	98.6				
352	182000	517	177408	97.5				
363	184000	507	182952	99.4				

Linear regression formula for calculating tensile strength is on previous page

As can be seen from Tables 2.12A and 2.12B:

Linear regression formula provides 97.5 to 99.9% accuracy in calculating tensile strength

Statistical formula provides 97.0 to 99.9% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 170 to 365 HB

Appendix 2

Tensile strength of AISI 1095 high-carbon steel versus Brinell hardness (3000-kgf applied load)

Table 2.13A. Linear regression formula for calculating tensile strength: $\sigma = 510 \times \text{HB} - 3605$

Brinell hardness HB	Tensile strength, psi		Accuracy in calcu- lating σ %	HB x σ_a	(HB) ²	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
	Ref 8, pp.44, 45								
192	95000	94315	99.3	18240000	36864	9.025E+09	510	-3605	0.9962
197	99000	96865	97.8	19503000	38809	9.801E+09			
248	120000	122875	97.7	29760000	61504	1.44E+10			
255	128000	126445	98.8	32640000	65025	1.638E+10			
262	130000	130015	<u>100</u>	34060000	68644	1.69E+10			
269	132000	133585	98.8	35508000	72361	1.742E+10			
269	134000	133585	99.7	36046000	72361	1.796E+10			
277	140000	137665	98.3	38780000	76729	1.96E+10			
293	142000	145825	<u>97.4</u>	41606000	85849	2.016E+10			
293	147000	145825	99.2	43071000	85849	2.161E+10			
302	148000	150415	98.4	44696000	91204	2.19E+10			
302	151000	150415	99.6	45602000	91204	2.28E+10			
311	151000	155005	<u>97.4</u>	46961000	96721	2.28E+10			
321	160000	160105	99.9	51360000	103041	2.56E+10			
331	165000	165205	99.9	54615000	109561	2.723E+10			
331	166000	165205	99.5	54946000	109561	2.756E+10			
331	168000	165205	98.3	55608000	109561	2.822E+10			
352	176000	175915	<u>100</u>	61952000	123904	3.098E+10			
363	184000	181525	98.7	66792000	131769	3.386E+10			
5,499	2,736,000			811746000	1630521	4.042E+11			

Statistical formula for calculating tensile strength is on the next page

Appendix 2

Tensile strength of AISI 1095 high-carbon steel versus Brinell hardness (3000-kgf applied load)

Table 2.13B. Statistical formula for calculating tensile strength: $\sigma = 498 \times \text{HB}$

Brinell hardness HB	Tensile strength σ_a , psi	Strength-to-hardness ratio σ_a / HB	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ/HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, pp.44, 45								
192	95000	495	95616	99.4	5,499	2,736,000	498	$\sigma = 498 \times \text{HB}$
197	99000	503	98106	99.1				
248	120000	484	123504	<u>97.2</u>				
255	128000	502	126990	99.2				
262	130000	496	130476	99.6				
269	132000	491	133962	98.5				
269	134000	498	133962	<u>100</u>				
277	140000	505	137946	98.5				
293	142000	485	145914	97.3				
293	147000	502	145914	99.3				
302	148000	490	150396	98.4				
302	151000	500	150396	99.6				
311	151000	486	154878	97.5				
321	160000	498	159858	99.9				
331	165000	498	164838	99.9				
331	166000	502	164838	99.3				
331	168000	508	164838	98.1				
352	176000	500	175296	99.6				
363	184000	507	180774	98.2				

Linear regression formula for calculating tensile strength is on previous page

As can be seen from Tables 2.13A and 2.13B:

Linear regression formula provides 97.4 to 100% accuracy in calculating tensile strength

Statistical formula provides 97.2 to 100% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 190 to 365 HB

Appendix 2

Tensile strength of AISI 1117 free-machining steel versus Brinell hardness (3000-kgf applied load)

Table 2.14A. Linear regression formula for calculating tensile strength: $\sigma = 479 \times \text{HB} + 2674$

Brinell hardness HB	Tensile strength, psi		Accuracy in calculating σ %	HB x σ_a	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, pp.49, 50							479	2674	0.9937
111	55000	55843	98.5	6105000	12321	3.025E+09			
116	58000	58238	99.6	6728000	13456	3.364E+09			
121	60000	60633	99.0	7260000	14641	3.6E+09			
121	62000	60633	97.8	7502000	14641	3.844E+09			
121	62300	60633	<u>97.3</u>	7538300	14641	3.881E+09			
126	63750	63028	98.9	8032500	15876	4.064E+09			
131	65000	65423	99.4	8515000	17161	4.225E+09			
137	67000	68297	98.1	9179000	18769	4.489E+09			
137	67750	68297	99.2	9281750	18769	4.59E+09			
137	68000	68297	99.6	9316000	18769	4.624E+09			
137	69000	68297	99.0	9453000	18769	4.761E+09			
143	69750	71171	98.0	9974250	20449	4.865E+09			
143	70000	71171	98.4	10010000	20449	4.9E+09			
143	71000	71171	<u>99.8</u>	10153000	20449	5.041E+09			
149	74750	74045	99.1	11137750	22201	5.588E+09			
149	75000	74045	98.7	11175000	22201	5.625E+09			
156	78000	77398	99.2	12168000	24336	6.084E+09			
163	80000	80751	99.1	13040000	26569	6.4E+09			
170	86000	84104	97.8	14620000	28900	7.396E+09			
183	89500	90331	99.1	16378500	33489	8.01E+09			
2,794	1,391,800			197567050	396856	9.838E+10			

Statistical formula for calculating tensile strength is on the next page

Appendix 2

Tensile strength of AISI 1117 free-machining steel versus Brinell hardness (3000-kgf applied load)

Table 2.14B. Statistical formula for calculating tensile strength: $\sigma = 498 \times \text{HB}$

Brinell hardness HB	Tensile strength σ_a , psi	Strength-to-hardness ratio σ_a / HB	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ/HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, pp.49, 50					2,794	1,391,800	498	$\sigma = 498 \times \text{HB}$
111	55000	495	55278	99.5				
116	58000	500	57768	99.6				
121	60000	496	60258	99.6				
121	62000	512	60258	97.2				
121	62300	515	60258	96.7				
126	63750	506	62748	98.4				
131	65000	496	65238	99.6				
137	67000	489	68226	98.2				
137	67750	495	68226	99.3				
137	68000	496	68226	99.7				
137	69000	504	68226	98.9				
143	69750	488	71214	97.9				
143	70000	490	71214	98.3				
143	71000	497	71214	99.7				
149	74750	502	74202	99.3				
149	75000	503	74202	98.9				
156	78000	500	77688	99.6				
163	80000	491	81174	98.6				
170	86000	506	84660	98.4				
183	89500	489	91134	98.2				

Linear regression formula for calculating tensile strength is on previous page

As can be seen from Tables 2.14A and 2.14B:

Linear regression formula provides 97.3 to 99.8% accuracy in calculating tensile strength

Statistical formula provides 96.7 to 99.7% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 110 to 185 HB

Appendix 2

Tensile strength of AISI 1118 free-machining steel versus Brinell hardness (3000-kgf applied load)

Table 2.15A. Linear regression formula for calculating tensile strength: $\sigma = 508 \times \text{HB} - 1619$

Brinell hardness HB	Tensile strength, psi		Accuracy in calculating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, pp.49, 50							508	-1619	0.9983
111	55000	54769	99.6	6105000	12321	3.025E+09			
116	58000	57309	98.8	6728000	13456	3.364E+09			
121	60000	59849	99.7	7260000	14641	3.6E+09			
126	64000	62389	97.5	8064000	15876	4.096E+09			
131	65000	64929	<u>99.9</u>	8515000	17161	4.225E+09			
131	65300	64929	99.4	8554300	17161	4.264E+09			
131	66250	64929	98.0	8678750	17161	4.389E+09			
137	68500	67977	99.2	9384500	18769	4.692E+09			
143	69000	71025	<u>97.1</u>	9867000	20449	4.761E+09			
143	69250	71025	97.5	9902750	20449	4.796E+09			
143	70000	71025	98.6	10010000	20449	4.9E+09			
143	70500	71025	99.3	10081500	20449	4.97E+09			
149	75000	74073	98.8	11175000	22201	5.625E+09			
149	76000	74073	97.5	11324000	22201	5.776E+09			
156	77000	77629	99.2	12012000	24336	5.929E+09			
163	80000	81185	98.5	13040000	26569	6.4E+09			
167	82250	83217	98.8	13735750	27889	6.765E+09			
207	102500	103537	99.0	21217500	42849	1.051E+10			
285	144500	143161	99.1	41182500	81225	2.088E+10			
2,852	1,418,050			226837550	455612	1.13E+11			

Statistical formula for calculating tensile strength is on the next page

Appendix 2

Tensile strength of AISI 1118 free-machining steel versus Brinell hardness (3000-kgf applied load)

Table 2.15B. Statistical formula for calculating tensile strength: $\sigma = 497 \times \text{HB}$

Brinell hardness HB	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ/HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, pp.49, 50		σ_a / HB	σ , psi					
111	55000	495	55167	99.7	2,852	1,418,050	497	$\sigma = 497 \times \text{HB}$
116	58000	500	57652	99.4				
121	60000	496	60137	99.8				
126	64000	508	62622	97.8				
131	65000	496	65107	99.8				
131	65300	498	65107	99.7				
131	66250	506	65107	98.3				
137	68500	500	68089	99.4				
143	69000	483	71071	97.1				
143	69250	484	71071	97.4				
143	70000	490	71071	98.5				
143	70500	493	71071	99.2				
149	75000	503	74053	98.7				
149	76000	510	74053	97.4				
156	77000	494	77532	99.3				
163	80000	491	81011	98.8				
167	82250	493	82999	99.1				
207	102500	495	102879	99.6				
285	144500	507	141645	98.0				

Linear regression formula for calculating tensile strength is on previous page

As can be seen from Tables 2.15A and 2.15B:

Linear regression formula provides 97.1 to 99.9% accuracy in calculating tensile strength

Statistical formula provides 97.1 to 99.8% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 110 to 285 HB

Appendix 2

Tensile strength of AISI 1137 free-machining steel versus Brinell hardness (3000-kgf applied load)

Table 2.16A. Linear regression formula for calculating tensile strength: $\sigma = 486 \times \text{HB} + 1474$

Brinell hardness HB	Tensile strength, psi		Accuracy in calculating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, pp.57, 58							486	1474	0.9933
163	80000	80692	99.1	13040000	26569	6.4E+09			
170	85000	84094	98.9	14450000	28900	7.225E+09			
174	85000	86038	98.8	14790000	30276	7.225E+09			
179	88000	88468	99.5	15752000	32041	7.744E+09			
179	90000	88468	98.3	16110000	32041	8.1E+09			
187	95000	92356	<u>97.2</u>	17765000	34969	9.025E+09			
192	94000	94786	99.2	18048000	36864	8.836E+09			
192	95000	94786	99.8	18240000	36864	9.025E+09			
197	96000	97216	98.7	18912000	38809	9.216E+09			
197	97000	97216	99.8	19109000	38809	9.409E+09			
197	98000	97216	99.2	19306000	38809	9.604E+09			
197	100000	97216	<u>97.2</u>	19700000	38809	1E+10			
201	98000	99160	98.8	19698000	40401	9.604E+09			
201	100000	99160	99.2	20100000	40401	1E+10			
207	101000	102076	98.9	20907000	42849	1.02E+10			
212	105000	104506	99.5	22260000	44944	1.103E+10			
217	105000	106936	98.2	22785000	47089	1.103E+10			
223	108000	109852	98.3	24084000	49729	1.166E+10			
229	110000	112768	97.5	25190000	52441	1.21E+10			
229	112000	112768	99.3	25648000	52441	1.254E+10			
248	122000	122002	<u>100</u>	30256000	61504	1.488E+10			
255	128000	125404	98.0	32640000	65025	1.638E+10			
262	130000	128806	99.1	34060000	68644	1.69E+10			
4,708	2,322,000			482850000	979228	2.381E+11			

Statistical formula for calculating tensile strength is on the next page

Appendix 2

Tensile strength of AISI 1137 free-machining steel versus Brinell hardness (3000-kgf applied load)

Table 2.16B. Statistical formula for calculating tensile strength: $\sigma = 493 \times \text{HB}$

Brinell hardness HB	Tensile strength σ_a , psi	Strength-to-hardness ratio σ_a / HB	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ/HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, pp.57, 58					4,708	2,322,000	493	$\sigma = 493 \times \text{HB}$
163	80000	491	80359	99.6				
170	85000	500	83810	98.6				
174	85000	489	85782	99.1				
179	88000	492	88247	99.7				
179	90000	503	88247	98.1				
187	95000	508	92191	<u>97.0</u>				
192	94000	490	94656	99.3				
192	95000	495	94656	99.6				
197	96000	487	97121	98.8				
197	97000	492	97121	<u>99.9</u>				
197	98000	497	97121	99.1				
197	100000	508	97121	97.1				
201	98000	488	99093	98.9				
201	100000	498	99093	99.1				
207	101000	488	102051	99.0				
212	105000	495	104516	99.5				
217	105000	484	106981	98.1				
223	108000	484	109939	98.2				
229	110000	480	112897	97.4				
229	112000	489	112897	99.2				
248	122000	492	122264	99.8				
255	128000	502	125715	98.2				
262	130000	496	129166	99.4				

Linear regression formula for calculating tensile strength is on previous page

As can be seen from Tables 2.16A and 2.16B:

Linear regression formula provides 97.2 to 100% accuracy in calculating tensile strength

Statistical formula provides 97.0 to 99.9% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 160 to 265 HB

Appendix 2

Tensile strength of AISI 1141 free-machining steel versus Brinell hardness (3000-kgf applied load)

Table 2.17A. Linear regression formula for calculating tensile strength: $\sigma = 475 \times \text{HB} + 5151$

Brinell hardness HB	Tensile strength, psi		Accuracy in calculating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, pp.59, 61							475	5151	0.9942
170	85000	85901	99.0	14450000	28900	7.225E+09			
179	90000	90176	99.8	16110000	32041	8.1E+09			
187	94000	93976	<u>100</u>	17578000	34969	8.836E+09			
187	95000	93976	98.9	17765000	34969	9.025E+09			
192	96000	96351	99.6	18432000	36864	9.216E+09			
192	98000	96351	98.3	18816000	36864	9.604E+09			
197	96000	98726	<u>97.2</u>	18912000	38809	9.216E+09			
197	100000	98726	98.7	19700000	38809	1E+10			
201	100000	100626	99.4	20100000	40401	1E+10			
201	101000	100626	99.6	20301000	40401	1.02E+10			
201	102000	100626	98.7	20502000	40401	1.04E+10			
207	103000	103476	99.5	21321000	42849	1.061E+10			
212	105000	105851	99.2	22260000	44944	1.103E+10			
212	107000	105851	98.9	22684000	44944	1.145E+10			
217	108000	108226	99.8	23436000	47089	1.166E+10			
223	110000	111076	99.0	24530000	49729	1.21E+10			
223	112000	111076	99.2	24976000	49729	1.254E+10			
235	116000	116776	99.3	27260000	55225	1.346E+10			
262	130000	129601	99.7	34060000	68644	1.69E+10			
3,895	1,948,000			403193000	806581	2.016E+11			

Statistical formula for calculating tensile strength is on the next page

Appendix 2

Tensile strength of AISI 1141 free-machining steel versus Brinell hardness (3000-kgf applied load)

Table 2.17B. Statistical formula for calculating tensile strength: $\sigma = 500 \times \text{HB}$

Brinell hardness HB	Tensile strength σ _a , psi	Strength-to-hardness ratio σ _a / HB	Tensile strength calculated by the above formula σ, psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ/HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ, psi		
Ref 8, pp.59, 61								
170	85000	500	85000	100	3,895	1,948,000	500	σ = 500 x HB
179	90000	503	89500	99.4				
187	94000	503	93500	99.5				
187	95000	508	93500	98.4				
192	96000	500	96000	100				
192	98000	510	96000	98.0				
197	96000	487	98500	97.5				
197	100000	508	98500	98.5				
201	100000	498	100500	99.5				
201	101000	502	100500	99.5				
201	102000	507	100500	98.5				
207	103000	498	103500	99.5				
212	105000	495	106000	99.1				
212	107000	505	106000	99.1				
217	108000	498	108500	99.5				
223	110000	493	111500	98.7				
223	112000	502	111500	99.6				
235	116000	494	117500	98.7				
262	130000	496	131000	99.2				

Linear regression formula for calculating tensile strength is on previous page

As can be seen from Tables 2.17A and 2.17B:

Linear regression formula provides 97.2 to 100% accuracy in calculating tensile strength

Statistical formula provides 97.5 to 100% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 170 to 265 HB

Appendix 2

Tensile strength of AISI 1144 free-machining steel versus Brinell hardness (3000-kgf applied load)

Table 2.18A. Linear regression formula for calculating tensile strength: $\sigma = 452 \times \text{HB} + 8254$

Brinell hardness HB	Tensile strength, psi		Accuracy in calculating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, pp.60, 61							452	8254	0.9911
167	85000	83738	98.5	14195000	27889	7.225E+09			
179	90000	89162	99.1	16110000	32041	8.1E+09			
183	89000	90970	<u>97.8</u>	16287000	33489	7.921E+09			
192	94000	95038	98.9	18048000	36864	8.836E+09			
192	96000	95038	99.0	18432000	36864	9.216E+09			
197	97000	97298	99.7	19109000	38809	9.409E+09			
201	98000	99106	98.9	19698000	40401	9.604E+09			
207	101000	101818	99.2	20907000	42849	1.02E+10			
207	102000	101818	<u>99.8</u>	21114000	42849	1.04E+10			
212	103000	104078	99.0	21836000	44944	1.061E+10			
212	105000	104078	99.1	22260000	44944	1.103E+10			
217	108000	106338	98.5	23436000	47089	1.166E+10			
223	110000	109050	99.1	24530000	49729	1.21E+10			
235	114000	114474	99.6	26790000	55225	1.3E+10			
2,824	1,392,000			282752000	573986	1.393E+11			

Table 2.18B. Statistical formula for calculating tensile strength: $\sigma = 493 \times \text{HB}$

Brinell hardness HB	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ/HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, pp.60, 61		σ_a / HB						
167	85000	509	82331	<u>96.9</u>	2,824	1,392,000	493	$\sigma = 493 \times \text{HB}$
179	90000	503	88247	98.1				
183	89000	486	90219	98.6				
192	94000	490	94656	99.3				
192	96000	500	94656	98.6				
197	97000	492	97121	99.9				
201	98000	488	99093	98.9				
207	101000	488	102051	99.0				
207	102000	493	102051	<u>100</u>				
212	103000	486	104516	98.5				
212	105000	495	104516	99.5				
217	108000	498	106981	99.1				
223	110000	493	109939	99.9				
235	114000	485	115855	98.4				

As can be seen from Tables 2.18A and 2.18B:

Linear regression formula provides 97.8 to 99.8% accuracy in calculating tensile strength

Statistical formula provides 96.9 to 100% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 165 to 235 HB

Appendix 2

Tensile strength of AISI 1211, 1212, 1213, and 1215 free-machining resulfurized
and rephosphorized steels versus Brinell hardness (3000-kgf applied load)

Table 2.19A. Linear regression formula for calculating tensile strength: $\sigma = 478 \times \text{HB} - 2354$

Brinell hardness HB	Tensile strength, psi		Accuracy in calcu- lating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, p.63									
121	55000	55484	99.1	6655000	14641	3.025E+09	478	-2354	0.9988
121	56000	55484	99.1	6776000	14641	3.136E+09			
163	75000	75560	99.3	12225000	26569	5.625E+09			
167	78000	77472	99.3	13026000	27889	6.084E+09			
572	264,000			38682000	83740	1.787E+10			

Table 2.19B. Statistical formula for calculating tensile strength: $\sigma = 462 \times \text{HB}$

Brinell hardness HB	Tensile strength σ _a , psi	Strength-to-hardness ratio σ _a / HB	Tensile strength calculated by the above formula σ, psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ/HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ, psi		
Ref 8, p.63								
121	55000	455	55902	98.4	572	264,000	462	σ = 462 x HB
121	56000	463	55902	99.8				
163	75000	460	75306	99.6				
167	78000	467	77154	98.9				

As can be seen from Tables 2.19A and 2.19B:

Linear regression formula provides 99.1 to 99.3 % accuracy in calculating tensile strength

Statistical formula provides 98.4 to 99.8 % accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 120 to 170 HB

Appendix 2

Tensile strength of AISI 1547 and 1548 high-manganese steels versus Brinell hardness (3000-kgf applied load)

Table 2.20A. Linear regression formula for calculating tensile strength: $\sigma = 511 \times \text{HB} - 4240$

Brinell hardness HB	Tensile strength, psi		Accuracy in calculating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, pp.4, 70									
192	93500	93872	99.6	2.E+07	36864	8.74E+09	511	-4240	0.9919
192	94000	93872	99.9	2.E+07	36864	8.84E+09			
197	96000	96427	99.6	2.E+07	38809	9.22E+09			
207	103000	101537	98.6	2.E+07	42849	1.06E+10			
217	106000	106647	99.4	2.E+07	47089	1.12E+10			
217	106500	106647	99.9	2.E+07	47089	1.13E+10			
1,222	599,000			1.E+08	249564	6E+10			

Table 2.20B. Statistical formula for calculating tensile strength: $\sigma = 490 \times \text{HB}$

Brinell hardness HB	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ/HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, pp.4, 70		σ_a / HB	σ , psi	%				
192	93500	487	94080	99.4	1,222	599,000	490	$\sigma = 490 \times \text{HB}$
192	94000	490	94080	99.9				
197	96000	487	96530	99.5				
207	103000	498	101430	98.5				
217	106000	488	106330	99.7				
217	106500	491	106330	99.8				

As can be seen from Tables 2.20A and 2.20B:

Linear regression formula provides 98.6 to 99.9 % accuracy in calculating tensile strength

Statistical formula provides 98.5 to 99.9 % accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 190 to 220 HB

APPENDIX 3. ALLOY STEELS

TENSILE STRENGTH versus BRINELL HARDNESS

Tables 3.1A and 3.1B. AISI 1340 and 1340H manganese steels

Tables 3.2A and 3.2B. AISI 4027 molybdenum steel

Tables 3.3A and 3.3B. AISI 4419 and 4419H molybdenum steels

Tables 3.4A and 3.4B. AISI 4118 and 4118H chromium-molybdenum steels

Tables 3.5A and 3.5B. AISI 4130 and 4130H chromium-molybdenum steels

Tables 3.6A and 3.6B. AISI 4140 and 4140H chromium-molybdenum steels

Tables 3.7A and 3.7B. AISI 4150 and 4150H chromium-molybdenum steels

Tables 3.8A and 3.8B. AISI 4620 and 4620H nickel-molybdenum steels

Tables 3.9A and 3.9B. AISI 4820 and 4820H nickel-molybdenum steels

Tables 3.10A and 3.10B. AISI 5140 and 5140H chromium steels

Tables 3.11A and 3.11B. AISI 5150 and 5150H chromium steels

Tables 3.12A and 3.12B. AISI 5160, 5160H, 51B60, and 51B60H chromium steels

Tables 3.13A and 3.13B. AISI 6150 and 6150H chromium-vanadium steels

Tables 3.14A and 3.14B. AISI 4320 and 4320H nickel-chromium-molybdenum steels

Tables 3.15A and 3.15B. AISI 4340, 4340H, E4340, and E4340H nickel-chromium-molybdenum steels

Tables 3.16A and 3.16B. AISI 4718 and 4718H nickel-chromium-molybdenum steels

Tables 3.17A and 3.17B. AISI 8620, and 8620H nickel-chromium-molybdenum steels

Tables 3.18A and 3.18B. AISI 8630, 8630H, and 86B30H nickel-chromium-molybdenum steels

Tables 3.19A and 3.19B. AISI 8640 and 8640H nickel-chromium-molybdenum steels

Tables 3.20A and 3.20B. AISI 8642 and 8642H nickel-chromium-molybdenum steels

Tables 3.21A and 3.21B. AISI 8650, 8650H, and 86B50 nickel-chromium-molybdenum steels

Tables 3.22A and 3.22B. AISI 8740 and 8740H nickel-chromium-molybdenum steels

Tables 3.23A and 3.23B. AISI E9310 and E9310H nickel-chromium-molybdenum steels

Tables 3.24A and 3.24B. AISI 9840 nickel-chromium-molybdenum steel

Tables 3.25A and 3.25B. AISI 9255 silicon-manganese steel

Appendix 3

Tensile strength of AISI 1340 and 1340H manganese steels versus Brinell hardness (3000-kgf applied load)

Table 3.1A. Linear regression formula for calculating tensile strength: $\sigma = 494 \times \text{HB} - 1006$

Brinell hardness HB	Tensile strength, psi		Accuracy in calculating σ %	HB x σ_a	(HB) ²	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, p.84							494	-1006	0.9925
207	102000	101252	99.3	21114000	42849	1.04E+10			
212	102000	103722	98.3	21624000	44944	1.04E+10			
217	106000	106192	99.8	23002000	47089	1.124E+10			
217	109000	106192	<u>97.4</u>	23653000	47089	1.188E+10			
229	112000	112120	99.9	25648000	52441	1.254E+10			
241	116000	118048	98.3	27956000	58081	1.346E+10			
241	118000	118048	<u>100</u>	28438000	58081	1.392E+10			
248	120000	121506	98.8	29760000	61504	1.44E+10			
248	121000	121506	99.6	30008000	61504	1.464E+10			
255	127000	124964	98.4	32385000	65025	1.613E+10			
269	132000	131880	99.9	35508000	72361	1.742E+10			
285	138000	139784	98.7	39330000	81225	1.904E+10			
285	142000	139784	98.4	40470000	81225	2.016E+10			
3,154	1,545,000			378896000	773418	1.857E+11			

Table 3.1B. Statistical formula for calculating tensile strength: $\sigma = 490 \times \text{HB}$

Brinell hardness HB	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, p.84		σ_a / HB						
207	102000	493	101430	99.4	3,154	1,545,000	490	$\sigma = 490 \times \text{HB}$
212	102000	481	103880	98.2				
217	106000	488	106330	99.7				
217	109000	502	106330	<u>97.6</u>				
229	112000	489	112210	99.8				
241	116000	481	118090	98.2				
241	118000	490	118090	<u>99.9</u>				
248	120000	484	121520	98.7				
248	121000	488	121520	99.6				
255	127000	498	124950	98.4				
269	132000	491	131810	<u>99.9</u>				
285	138000	484	139650	98.8				
285	142000	498	139650	98.3				

As can be seen from Tables 3.1A and 3.1B:

Linear regression formula provides 97.4 to 100% accuracy in calculating tensile strength

Statistical formula provides 97.6 to 99.9% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 200 to 285 HB

Appendix 3

Tensile strength of AISI 4027 molybdenum steel versus Brinell hardness (3000-kgf applied load)

Table 3.2A. Linear regression formula for calculating tensile strength: $\sigma = 457 \times \text{HB} + 8389$

Brinell hardness HB	Tensile strength, psi		Accuracy in calculating σ %	HB x σ_a	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, p.100									
192	95000	96133	98.8	18240000	36864	9.025E+09	457	8389	0.9984
201	100000	100246	99.8	20100000	40401	1E+10			
201	101000	100246	99.3	20301000	40401	1.02E+10			
212	104000	105273	98.8	22048000	44944	1.082E+10			
223	111000	110300	99.4	24753000	49729	1.232E+10			
229	114000	113042	99.2	26106000	52441	1.3E+10			
262	130000	128123	98.6	34060000	68644	1.69E+10			
285	139000	138634	99.7	39615000	81225	1.932E+10			
302	144000	146403	98.4	43488000	91204	2.074E+10			
311	150000	150516	99.7	46650000	96721	2.25E+10			
321	156000	155086	99.4	50076000	103041	2.434E+10			
2,739	1,344,000			345437000	705615	1.692E+11			

Table 3.2B. Statistical formula for calculating tensile strength: $\sigma = 491 \times \text{HB}$

Brinell hardness HB	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, p.100		σ_a / HB	σ , psi					
192	95000	495	94272	99.2	2,739	1,344,000	491	$\sigma = 491 \times \text{HB}$
201	100000	498	98691	98.7				
201	101000	502	98691	97.7				
212	104000	491	104092	99.9				
223	111000	498	109493	98.6				
229	114000	498	112439	98.6				
262	130000	496	128642	99.0				
285	139000	488	139935	99.3				
302	144000	477	148282	97.1				
311	150000	482	152701	98.2				
321	156000	486	157611	99.0				

As can be seen from Tables 3.2A and 3.2B:

Linear regression formula provides 98.4 to 99.8% accuracy in calculating tensile strength

Statistical formula provides 97.1 to 99.9% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 190 to 325 HB

Appendix 3

Tensile strength of AISI 4419 and 4419H molybdenum steels versus Brinell hardness (3000-kgf applied load)

Table 3.3A. Linear regression formula for calculating tensile strength: $\sigma = 486 \times \text{HB} + 726$

Brinell hardness HB	Tensile strength, psi		Accuracy in calculating σ %	HB x σ_a	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, pp.137, 138									
143	72000	70224	97.5	10296000	20449	5.184E+09	486	726	0.9900
143	73000	70224	<u>96.2</u>	10439000	20449	5.329E+09			
170	84000	83346	99.2	14280000	28900	7.056E+09			
179	86000	87720	98.0	15394000	32041	7.396E+09			
192	92000	94038	97.8	17664000	36864	8.464E+09			
197	94000	96468	97.4	18518000	38809	8.836E+09			
201	96000	98412	97.5	19296000	40401	9.216E+09			
201	97000	98412	98.6	19497000	40401	9.409E+09			
201	98500	98412	<u>99.9</u>	19798500	40401	9.702E+09			
212	102750	103758	99.0	21783000	44944	1.056E+10			
212	103000	103758	99.3	21836000	44944	1.061E+10			
217	106500	106188	99.7	23110500	47089	1.134E+10			
235	118500	114936	97.0	27847500	55225	1.404E+10			
241	120500	117852	97.8	29040500	58081	1.452E+10			
2,744	1,343,750			268800000	548998	1.317E+11			

Table 3.3B. Statistical formula for calculating tensile strength: $\sigma = 490 \times \text{HB}$

Brinell hardness HB	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, pp.137, 138		σ_a / HB	σ , psi					
143	72000	503	70070	97.3	2,744	1,343,750	490	$\sigma = 490 \times \text{HB}$
143	73000	510	70070	<u>96.0</u>				
170	84000	494	83300	99.2				
179	86000	480	87710	98.1				
192	92000	479	94080	97.8				
197	94000	477	96530	97.4				
201	96000	478	98490	97.5				
201	97000	483	98490	98.5				
201	98500	490	98490	<u>100</u>				
212	102750	485	103880	98.9				
212	103000	486	103880	99.2				
217	106500	491	106330	99.8				
235	118500	504	115150	97.2				
241	120500	500	118090	98.0				

As can be seen from Tables 3.3A and 3.3B:

Linear regression formula provides 96.2 to 99.9% accuracy in calculating tensile strength

Statistical formula provides 96.0 to 100% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 140 to 245 HB

Appendix 3

Tensile strength of AISI 4118 and 4118H chromium-molybdenum steels vs. Brinell hardness (3000-kgf applied load)

Table 3.4A. Linear regression formula for calculating tensile strength: $\sigma = 518 \times \text{HB} - 6112$

Brinell hardness HB	Tensile strength, psi		Accuracy in calculating σ %	HB x σ_a	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, pp.106, 107							518	-6112	0.9986
170	85000	81948	<u>96.4</u>	14450000	28900	7.225E+09			
187	89500	90754	98.6	16736500	34969	8.01E+09			
192	93000	93344	99.6	17856000	36864	8.649E+09			
192	93500	93344	<u>99.8</u>	17952000	36864	8.742E+09			
201	97000	98006	99.0	19497000	40401	9.409E+09			
235	115000	115618	99.5	27025000	55225	1.323E+10			
241	119000	118726	99.8	28679000	58081	1.416E+10			
277	138000	137374	99.5	38226000	76729	1.904E+10			
293	143000	145662	98.2	41899000	85849	2.045E+10			
352	178000	176224	99.0	62656000	123904	3.168E+10			
2,340	1,151,000			284976500	577786	1.406E+11			

Table 3.4B. Statistical formula for calculating tensile strength: $\sigma = 492 \times \text{HB}$

Brinell hardness HB	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, pp.106, 107		σ_a / HB	σ , psi	%				
170	85000	500	83640	98.4	2,340	1,151,000	492	$\sigma = 492 \times \text{HB}$
187	89500	479	92004	<u>97.3</u>				
192	93000	484	94464	98.5				
192	93500	487	94464	99.0				
201	97000	483	98892	98.1				
235	115000	489	115620	99.5				
241	119000	494	118572	<u>99.6</u>				
277	138000	498	136284	98.8				
293	143000	488	144156	99.2				
352	178000	506	173184	<u>97.3</u>				

As can be seen from Tables 3.4A and 3.4B:

Linear regression formula provides 96.4 to 99.8% accuracy in calculating tensile strength

Statistical formula provides 97.3 to 99.6% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 170 to 355 HB

Appendix 3

Tensile strength of AISI 4130 and 4130H chromium-molybdenum steels vs. Brinell hardness (3000-kgf applied load)

Table 3.5A. Linear regression formula for calculating tensile strength: $\sigma = 500 \times \text{HB} - 1206$

Brinell hardness HB	Tensile strength, psi		Accuracy in calculating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, pp.109, 110							500	-1206	0.9994
197	97000	97294	99.7	19109000	38809	9.409E+09			
217	106000	107294	98.8	23002000	47089	1.124E+10			
229	114000	113294	99.4	26106000	52441	1.3E+10			
235	116000	116294	99.7	27260000	55225	1.346E+10			
241	122000	119294	97.8	29402000	58081	1.488E+10			
262	128000	129794	98.6	33536000	68644	1.638E+10			
269	133000	133294	99.8	35777000	72361	1.769E+10			
293	144000	145294	99.1	42192000	85849	2.074E+10			
302	151000	149794	99.2	45602000	91204	2.28E+10			
305	150000	151294	99.1	45750000	93025	2.25E+10			
321	161000	159294	98.9	51681000	103041	2.592E+10			
331	166000	164294	99.0	54946000	109561	2.756E+10			
360	178000	178794	99.6	64080000	129600	3.168E+10	Hardness and tensile strength data in this section are from Table 2, Ref 7, p.431.		
385	192000	191294	99.6	73920000	148225	3.686E+10			
418	206000	207794	99.1	86108000	174724	4.244E+10			
440	218000	218794	99.6	95920000	193600	4.752E+10			
450	225000	223794	99.5	101250000	202500	5.063E+10			
5,255	2,607,000			855641000	1723979	4.247E+11			

Statistical formula for calculating tensile strength is on the next page

Appendix 3

Tensile strength of AISI 4130 and 4130H chromium-molybdenum steels vs. Brinell hardness (3000-kgf applied load)

Table 3.5B. Statistical formula for calculating tensile strength: $\sigma = 496 \times \text{HB}$

Brinell hardness HB	Tensile strength σ_a , psi	Strength-to-hardness ratio σ_a / HB	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, pp.109, 110					5,255	2,607,000	496	$\sigma = 496 \times \text{HB}$
197	97000	492	97712	99.3				
217	106000	488	107632	98.5				
229	114000	498	113584	99.6				
235	116000	494	116560	99.5				
241	122000	506	119536	98.0				
262	128000	489	129952	98.5				
269	133000	494	133424	99.7				
293	144000	491	145328	99.1				
302	151000	500	149792	99.2				
305	150000	492	151280	99.2				
321	161000	502	159216	98.9				
331	166000	502	164176	98.9				
360	178000	494	178560	99.7	Hardness and tensile strength data in this section are from Table 2, Ref 7, p.431.			
385	192000	499	190960	99.5				
418	206000	493	207328	99.4				
440	218000	495	218240	99.9				
450	225000	500	223200	99.2				

Linear regression formula for calculating tensile strength is on previous page

As can be seen from Tables 3.5A and 3.5B:

Linear regression formula provides 97.8 to 99.8% accuracy in calculating tensile strength

Statistical formula provides 98.0 to 99.9% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 190 to 450 HB

Appendix 3

Tensile strength of AISI 4140 and 4140H chromium-molybdenum steels vs. Brinell hardness (3000-kgf applied load)

Table 3.6A. Linear regression formula for calculating tensile strength: $\sigma = 506 \times \text{HB} - 3456$

Brinell hardness HB	Tensile strength, psi		Accuracy in calcu- lating σ %	HB x σ_a	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
	Ref 8, pp.114, 115								
197	95000	96226	98.7	18715000	38809	9.025E+09	506	-3456	0.9991
229	112000	112418	99.6	25648000	52441	1.254E+10			
235	117000	115454	98.7	27495000	55225	1.369E+10			
241	118000	118490	99.6	28438000	58081	1.392E+10			
241	122000	118490	<u>97.1</u>	29402000	58081	1.488E+10			
262	128000	129116	99.1	33536000	68644	1.638E+10			
269	133000	132658	99.7	35777000	72361	1.769E+10			
277	136000	136706	99.5	37672000	76729	1.85E+10			
285	140000	140754	99.5	39900000	81225	1.96E+10			
285	141000	140754	99.8	40185000	81225	1.988E+10			
302	148000	149356	99.1	44696000	91204	2.19E+10			
311	156000	153910	98.7	48516000	96721	2.434E+10			
321	158000	158970	99.4	50718000	103041	2.496E+10			
341	167000	169090	98.8	56947000	116281	2.789E+10			
341	172000	169090	98.3	58652000	116281	2.958E+10			
388	188000	192872	97.5	72944000	150544	3.534E+10			
429	210000	213618	98.3	90090000	184041	4.41E+10			
455	230000	226774	98.6	104650000	207025	5.29E+10			
461	231000	229810	99.5	106491000	212521	5.336E+10			
495	250000	247014	98.8	123750000	245025	6.25E+10			
520	260000	259664	<u>99.9</u>	135200000	270400	6.76E+10			
534	270000	266748	98.8	144180000	285156	7.29E+10			
578	285000	289012	98.6	164730000	334084	8.123E+10			
7,997	3,967,000			2.E+09	3055145	7.547E+11			

Statistical formula for calculating tensile strength is on the next page

Appendix 3

Tensile strength of AISI 4140 and 4140H chromium-molybdenum steels vs. Brinell hardness (3000-kgf applied load)

Table 3.6B. Statistical formula for calculating tensile strength: $\sigma = 496 \times \text{HB}$

Brinell hardness HB	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, pp.114, 115		σ_a / HB						
197	95000	482	97712	97.2	7,997	3,967,000	496	$\sigma = 496 \times \text{HB}$
229	112000	489	113584	98.6				
235	117000	498	116560	99.6				
241	118000	490	119536	98.7				
241	122000	506	119536	98.0				
262	128000	489	129952	98.5				
269	133000	494	133424	99.7				
277	136000	491	137392	99.0				
285	140000	491	141360	99.0				
285	141000	495	141360	99.7				
302	148000	490	149792	98.8				
311	156000	502	154256	98.9				
321	158000	492	159216	99.2				
341	167000	490	169136	98.7				
341	172000	504	169136	98.3				
388	188000	485	192448	97.7				
429	210000	490	212784	98.7				
455	230000	505	225680	98.1				
461	231000	501	228656	99.0				
495	250000	505	245520	98.2				
520	260000	500	257920	99.2				
534	270000	506	264864	98.1				
578	285000	493	286688	99.4				

Linear regression formula for calculating tensile strength is on previous page

As can be seen from Tables 3.6A and 3.6B:

Linear regression formula provides 97.1 to 99.9% accuracy in calculating tensile strength

Statistical formula provides 97.2 to 99.7% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 190 to 580 HB

Appendix 3

Tensile strength of AISI 4150 and 4150H chromium-molybdenum steels vs. Brinell hardness (3000-kgf applied load)

Table 3.7A. Linear regression formula for calculating tensile strength: $\sigma = 527 \times \text{HB} - 8977$

Brinell hardness HB	Tensile strength, psi		Accuracy in calculating σ %	HB x σ_a	(HB) ²	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, p.121							527	-8977	0.9958
255	124000	125408	98.9	31620000	65025	1.538E+10			
269	132000	132786	99.4	35508000	72361	1.742E+10			
269	135000	132786	98.4	36315000	72361	1.823E+10			
285	141000	141218	99.8	40185000	81225	1.988E+10			
293	146000	145434	99.6	42778000	85849	2.132E+10			
302	148000	150177	98.6	44696000	91204	2.19E+10			
302	150000	150177	99.9	45300000	91204	2.25E+10			
311	159000	154920	97.4	49449000	96721	2.528E+10			
331	166000	165460	99.7	54946000	109561	2.756E+10			
341	169000	170730	99.0	57629000	116281	2.856E+10			
341	170000	170730	99.6	57970000	116281	2.89E+10			
352	175000	176527	99.1	61600000	123904	3.063E+10			
375	190000	188648	99.3	71250000	140625	3.61E+10			
4,026	2,005,000			6.E+08	1262602	3.136E+11			

Table 3.7B. Statistical formula for calculating tensile strength: $\sigma = 498 \times \text{HB}$

Brinell hardness HB	Tensile strength σ_a , psi	Strength-to-hardness ratio σ_a / HB	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref. 8, p. 121					4,026	2,005,000	498	$\sigma = 498 \times \text{HB}$
255	124000	486	126990	97.6				
269	132000	491	133962	98.5				
269	135000	502	133962	99.2				
285	141000	495	141930	99.3				
293	146000	498	145914	99.9				
302	148000	490	150396	98.4				
302	150000	497	150396	99.7				
311	159000	511	154878	97.4				
331	166000	502	164838	99.3				
341	169000	496	169818	99.5				
341	170000	499	169818	99.9				
352	175000	497	175296	99.8				
375	190000	507	186750	98.3				

As can be seen from Tables 3.7A and 3.7B:

Linear regression formula provides 97.4 to 99.9% accuracy in calculating tensile strength

Statistical formula provides 97.4 to 99.9% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 255 to 375 HB

Appendix 3

Tensile strength of AISI 4620 and 4620H nickel-molybdenum steels vs. Brinell hardness (3000-kgf applied load)

Table 3.8A. Linear regression formula for calculating tensile strength: $\sigma = 462 \times \text{HB} + 7075$

Brinell hardness HB	Tensile strength, psi		Accuracy in calculating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, pp.142-144									
149	74000	75913	97.5	11026000	22201	5.476E+09	462	7075	0.9980
170	84000	85615	98.1	14280000	28900	7.056E+09			
170	85000	85615	99.3	14450000	28900	7.225E+09			
187	96000	93469	<u>97.4</u>	17952000	34969	9.216E+09			
192	96000	95779	99.8	18432000	36864	9.216E+09			
192	98000	95779	97.7	18816000	36864	9.604E+09			
197	98000	98089	<u>99.9</u>	19306000	38809	9.604E+09			
235	115300	115645	99.7	27095500	55225	1.329E+10			
241	118000	118417	99.6	28438000	58081	1.392E+10			
248	122000	121651	99.7	30256000	61504	1.488E+10			
255	127000	124885	98.3	32385000	65025	1.613E+10			
285	137000	138745	98.7	39045000	81225	1.877E+10			
302	145000	146599	98.9	43790000	91204	2.103E+10			
302	147500	146599	99.4	44545000	91204	2.176E+10			
3125	1542800			359816500	730975	1.772E+11			

Table 3.8B. Statistical formula for calculating tensile strength: $\sigma = 494 \times \text{HB}$

Brinell hardness HB	Tensile strength σ_a , psi	Strength-to-hardness ratio σ_a / HB	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, pp.142-144								
149	74000	497	73606	99.5	3,125	1,542,800	494	$\sigma = 494 \times \text{HB}$
170	84000	494	83980	<u>100</u>				
170	85000	500	83980	98.8				
187	96000	513	92378	<u>96.2</u>				
192	96000	500	94848	98.8				
192	98000	510	94848	96.8				
197	98000	497	97318	99.3				
235	115300	491	116090	99.3				
241	118000	490	119054	99.1				
248	122000	492	122512	99.6				
255	127000	498	125970	99.2				
285	137000	481	140790	97.3				
302	145000	480	149188	97.2				
302	147500	488	149188	98.9				

As can be seen from Tables 3.8A and 3.8B:

Linear regression formula provides 97.4 to 99.9% accuracy in calculating tensile strength

Statistical formula provides 96.2 to 100% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 145 to 305 HB

Appendix 3

Tensile strength of AISI 4820 and 4820H nickel-molybdenum steels vs. Brinell hardness (3000-kgf applied load)

Table 3.9A. Linear regression formula for calculating tensile strength: $\sigma = 502 \times \text{HB} - 2994$

Brinell hardness HB	Tensile strength, psi		Accuracy in calcu- lating σ %	HB x σ_a	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, pp.152, 153							502	-2994	0.9990
197	99000	95900	<u>96.9</u>	19503000	38809	9.801E+09			
212	104000	103430	99.5	22048000	44944	1.082E+10			
223	107000	108952	98.2	23861000	49729	1.145E+10			
229	110000	111964	98.2	25190000	52441	1.21E+10			
235	117000	114976	98.3	27495000	55225	1.369E+10			
241	119000	117988	99.1	28679000	58081	1.416E+10			
269	130000	132044	98.5	34970000	72361	1.69E+10			
277	136000	136060	<u>100</u>	37672000	76729	1.85E+10			
331	163000	163168	99.9	53953000	109561	2.657E+10			
352	170000	173710	97.9	59840000	123904	2.89E+10			
363	178400	179232	99.5	64759200	131769	3.183E+10			
363	179000	179232	99.9	64977000	131769	3.204E+10			
388	191800	191782	<u>100</u>	74418400	150544	3.679E+10			
388	192600	191782	99.6	74728800	150544	3.709E+10			
401	197700	198308	99.7	79277700	160801	3.909E+10			
401	200500	198308	98.9	80400500	160801	4.02E+10			
415	205000	205336	99.8	85075000	172225	4.203E+10			
415	207500	205336	99.0	86112500	172225	4.306E+10			
5,700	2,807,500			942960100	1912462	4.65E+11			

Statistical formula for calculating tensile strength is on the next page

Appendix 3

Tensile strength of AISI 4820 and 4820H nickel-molybdenum steels vs. Brinell hardness (3000-kgf applied load)

Table 3.9B. Statistical formula for calculating tensile strength: $\sigma = 493 \times \text{HB}$

Brinell hardness HB	Tensile strength σ_a , psi	Strength-to-hardness ratio σ_a / HB	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, pp.152, 153								
197	99000	503	97121	98.1	5,700	2,807,500	493	$\sigma = 493 \times \text{HB}$
212	104000	491	104516	99.5				
223	107000	480	109939	<u>97.3</u>				
229	110000	480	112897	97.4				
235	117000	498	115855	99.0				
241	119000	494	118813	99.8				
269	130000	483	132617	98.0				
277	136000	491	136561	99.6				
331	163000	492	163183	99.9				
352	170000	483	173536	98.0				
363	178400	491	178959	99.7				
363	179000	493	178959	<u>100</u>				
388	191800	494	191284	99.7				
388	192600	496	191284	99.3				
401	197700	493	197693	<u>100</u>				
401	200500	500	197693	98.6				
415	205000	494	204595	99.8				
415	207500	500	204595	98.6				

Linear regression formula for calculating tensile strength is on previous page

As can be seen from Tables 3.9A and 3.9B:

Linear regression formula provides 96.9 to 100% accuracy in calculating tensile strength

Statistical formula provides 97.3 to 100% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 195 to 415 HB

Appendix 3

Tensile strength of AISI 5140 and 5140H chromium steels versus Brinell hardness (3000-kgf applied load)

Table 3.10A. Linear regression formula for calculating tensile strength: $\sigma = 454 \times \text{HB} + 9955$

Brinell hardness HB	Tensile strength, psi		Accuracy in calculating σ %	HB x σ_a	(HB) ²	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, p.174									
167	83000	85773	<u>96.8</u>	13861000	27889	6.889E+09	454	9955	0.9902
217	106000	108473	97.7	23002000	47089	1.124E+10			
217	111000	108473	97.7	24087000	47089	1.232E+10			
223	110000	111197	98.9	24530000	49729	1.21E+10			
223	113000	111197	98.4	25199000	49729	1.277E+10			
229	115000	113921	99.1	26335000	52441	1.323E+10			
235	116000	116645	99.4	27260000	55225	1.346E+10			
235	117000	116645	99.7	27495000	55225	1.369E+10			
235	120000	116645	97.2	28200000	55225	1.44E+10			
241	118000	119369	98.9	28438000	58081	1.392E+10			
241	120000	119369	99.5	28920000	58081	1.44E+10			
248	125000	122547	98.0	31000000	61504	1.563E+10			
255	128000	125725	98.2	32640000	65025	1.638E+10			
262	127000	128903	98.5	33274000	68644	1.613E+10			
269	130000	132081	98.4	34970000	72361	1.69E+10			
293	141000	142977	98.6	41313000	85849	1.988E+10			
302	147000	147063	<u>100</u>	44394000	91204	2.161E+10			
4,092	2,027,000			494918000	1000390	2.449E+11			

Statistical formula for calculating tensile strength is on the next page

Appendix 3

Tensile strength of AISI 5140 and 5140H chromium steels versus Brinell hardness (3000-kgf applied load)

Table 3.10B. Statistical formula for calculating tensile strength: $\sigma = 495 \times \text{HB}$

Brinell hardness HB	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, p.174		σ_a / HB						
167	83000	497	82665	99.6	4,092	2,027,000	495	$\sigma = 495 \times \text{HB}$
217	106000	488	107415	98.7				
217	111000	512	107415	<u>96.8</u>				
223	110000	493	110385	<u>99.7</u>				
223	113000	507	110385	97.7				
229	115000	502	113355	98.6				
235	116000	494	116325	<u>99.7</u>				
235	117000	498	116325	99.4				
235	120000	511	116325	96.9				
241	118000	490	119295	98.9				
241	120000	498	119295	99.4				
248	125000	504	122760	98.2				
255	128000	502	126225	98.6				
262	127000	485	129690	97.9				
269	130000	483	133155	97.6				
293	141000	481	145035	97.2				
302	147000	487	149490	98.3				

Linear regression formula for calculating tensile strength is on previous page

As can be seen from Tables 3.10A and 3.10B:

Linear regression formula provides 96.8 to 100% accuracy in calculating tensile strength

Statistical formula provides 96.8 to 99.7% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 165 to 305 HB

Appendix 3

Tensile strength of AISI 5150 and 5150H chromium steels versus Brinell hardness (3000-kgf applied load)

Table 3.11A. Linear regression formula for calculating tensile strength: $\sigma = 536 \times \text{HB} - 9150$

Brinell hardness HB	Tensile strength, psi		Accuracy in calculating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, p.176							536	-9150	0.9963
197	98000	96442	98.4	19306000	38809	9.604E+09			
235	115000	116810	98.5	27025000	55225	1.323E+10			
241	119000	120026	99.1	28679000	58081	1.416E+10			
241	120000	120026	<u>100</u>	28920000	58081	1.44E+10			
241	122000	120026	98.4	29402000	58081	1.488E+10			
248	123000	123778	99.4	30504000	61504	1.513E+10			
248	125000	123778	99.0	31000000	61504	1.563E+10			
255	126000	127530	98.8	32130000	65025	1.588E+10			
255	127000	127530	99.6	32385000	65025	1.613E+10			
255	128000	127530	99.6	32640000	65025	1.638E+10			
262	131000	131282	99.8	34322000	68644	1.716E+10			
269	136000	135034	99.3	36584000	72361	1.85E+10			
277	137000	139322	<u>98.3</u>	37949000	76729	1.877E+10			
285	144000	143610	99.7	41040000	81225	2.074E+10			
302	153000	152722	99.8	46206000	91204	2.341E+10			
311	159000	157546	99.1	49449000	96721	2.528E+10			
4122	2063000			537541000	1073244	2.693E+11			

Table 3.11B. Statistical formula for calculating tensile strength: $\sigma = 500 \times \text{HB}$

Brinell hardness HB	Tensile strength σ_a , psi	Strength-to-hardness ratio σ_a / HB	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, p.176					4,122	2,063,000	500	$\sigma = 500 \times \text{HB}$
197	98000	497	98500	99.5				
235	115000	489	117500	97.9				
241	119000	494	120500	98.8				
241	120000	498	120500	99.6				
241	122000	506	120500	98.8				
248	123000	496	124000	99.2				
248	125000	504	124000	99.2				
255	126000	494	127500	98.8				
255	127000	498	127500	99.6				
255	128000	502	127500	99.6				
262	131000	500	131000	<u>100</u>				
269	136000	506	134500	98.9				
277	137000	495	138500	98.9				
285	144000	505	142500	99.0				
302	153000	507	151000	98.7				
311	159000	511	155500	<u>97.8</u>				

As can be seen from Tables 3.11A and 3.11B:

Linear regression formula provides 98.3 to 100% accuracy in calculating tensile strength

Statistical formula provides 97.8 to 100% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 195 to 315 HB

Appendix 3

Tensile strength of AISI 5160, 5160H, 51B60, and 51B60H chromium steels
versus Brinell hardness (3000-kgf applied load)

Table 3.12A. Linear regression formula for calculating tensile strength: $\sigma = 480 \times \text{HB} + 4511$

Brinell hardness HB	Tensile strength, psi		Accuracy in calculating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, p.180									
241	120000	120191	99.8	28920000	58081	1.44E+10	480	4511	0.9917
262	129000	130271	99.0	33798000	68644	1.664E+10			
262	134000	130271	97.2	35108000	68644	1.796E+10			
269	133000	133631	99.5	35777000	72361	1.769E+10			
277	135000	137471	98.2	37395000	76729	1.823E+10			
285	140000	141311	99.1	39900000	81225	1.96E+10			
302	152000	149471	98.3	45904000	91204	2.31E+10			
341	166000	168191	98.7	56606000	116281	2.756E+10			
341	170000	168191	98.9	57970000	116281	2.89E+10			
2,580	1,279,000			371378000	749450	1.841E+11			

Table 3.12B. Statistical formula for calculating tensile strength: $\sigma = 496 \times \text{HB}$

Brinell hardness HB	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, p.180		σ_a / HB	σ , psi					
241	120000	498	119536	99.6	2,580	1,279,000	496	$\sigma = 496 \times \text{HB}$
262	129000	492	129952	99.3				
262	134000	511	129952	97.0				
269	133000	494	133424	99.7				
277	135000	487	137392	98.3				
285	140000	491	141360	99.0				
302	152000	503	149792	98.5				
341	166000	487	169136	98.1				
341	170000	499	169136	99.5				

As can be seen from Tables 3.12A and 3.12B:

Linear regression formula provides 97.2 to 99.8% accuracy in calculating tensile strength

Statistical formula provides 97.0 to 99.7% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 240 to 345 HB

Appendix 3

Tensile strength of AISI 6150 and 6150H chromium-vanadium steels vs. Brinell hardness (3000-kgf applied load)

Table 3.13A. Linear regression formula for calculating tensile strength: $\sigma = 496 \times \text{HB} + 878$

Brinell hardness HB	Tensile strength, psi		Accuracy in calculating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, p.184							496	878	0.9958
197	97000	98590	98.4	19109000	38809	9.409E+09			
241	122000	120414	98.7	29402000	58081	1.488E+10			
255	128000	127358	99.5	32640000	65025	1.638E+10			
262	130000	130830	99.4	34060000	68644	1.69E+10			
269	134000	134302	99.8	36046000	72361	1.796E+10			
269	136000	134302	98.8	36584000	72361	1.85E+10			
285	141000	142238	99.1	40185000	81225	1.988E+10			
293	141000	146206	<u>96.4</u>	41313000	85849	1.988E+10			
293	147000	146206	99.5	43071000	85849	2.161E+10			
293	148000	146206	98.8	43364000	85849	2.19E+10			
302	152000	150670	99.1	45904000	91204	2.31E+10			
311	158000	155134	98.2	49138000	96721	2.496E+10			
321	160000	160094	<u>99.9</u>	51360000	103041	2.56E+10			
331	166000	165054	99.4	54946000	109561	2.756E+10			
352	174000	175470	99.2	61248000	123904	3.028E+10			
363	180000	180926	99.5	65340000	131769	3.24E+10			
4,637	2,314,000			683710000	1370253	3.412E+11			

Table 3.13B. Statistical formula for calculating tensile strength: $\sigma = 499 \times \text{HB}$

Brinell hardness HB	Tensile strength σ_a , psi	Strength-to-hardness ratio σ_a / HB	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, p.184					4,637	2,314,000	499	$\sigma = 499 \times \text{HB}$
197	97000	492	98303	98.7				
241	122000	506	120259	98.6				
255	128000	502	127245	99.4				
262	130000	496	130738	99.4				
269	134000	498	134231	99.8				
269	136000	506	134231	98.7				
285	141000	495	142215	99.1				
293	141000	481	146207	<u>96.4</u>				
293	147000	502	146207	99.5				
293	148000	505	146207	98.8				
302	152000	503	150698	99.1				
311	158000	508	155189	98.2				
321	160000	498	160179	<u>99.9</u>				
331	166000	502	165169	99.5				
352	174000	494	175648	99.1				
363	180000	496	181137	99.4				

As can be seen from Tables 3.13A and 3.13B:

Linear regression formula provides 96.4 to 99.9% accuracy in calculating tensile strength

Statistical formula provides 96.4 to 99.9% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 195 to 365 HB

Appendix 3

Tensile strength of AISI 4320 and 4320H nickel-chromium-molybdenum steels
versus Brinell hardness (3000-kgf applied load)

Table 3.14A. Linear regression formula for calculating tensile strength: $\sigma = 499 \times \text{HB} - 774$

Brinell hardness HB	Tensile strength, psi		Accuracy in calcu- lating σ %	HB x σ_a	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, pp.128, 129							499	-774	0.9957
163	84000	80563	95.9	13692000	26569	7.056E+09			
201	102000	99525	97.6	20502000	40401	1.04E+10			
212	102000	105014	97.1	21624000	44944	1.04E+10			
235	115000	116491	98.7	27025000	55225	1.323E+10			
241	118000	119485	98.8	28438000	58081	1.392E+10			
248	120000	122978	97.6	29760000	61504	1.44E+10			
248	122000	122978	99.2	30256000	61504	1.488E+10			
255	130000	126471	97.3	33150000	65025	1.69E+10			
255	132000	126471	95.8	33660000	65025	1.742E+10			
293	146000	145433	99.6	42778000	85849	2.132E+10			
302	149000	149924	99.4	44998000	91204	2.22E+10			
302	152000	149924	98.6	45904000	91204	2.31E+10			
331	161000	164395	97.9	53291000	109561	2.592E+10			
341	167000	169385	98.6	56947000	116281	2.789E+10			
352	171000	174874	97.8	60192000	123904	2.924E+10			
375	180000	186351	96.6	67500000	140625	3.24E+10			
388	188000	192838	97.5	72944000	150544	3.534E+10			
415	212000	206311	97.3	87980000	172225	4.494E+10			
429	217000	213297	98.3	93093000	184041	4.709E+10			
429	218000	213297	97.8	93522000	184041	4.752E+10			
6,015	2,986,000			1.E+09	1927757	4.756E+11			

Statistical formula for calculating tensile strength is on the next page

Appendix 3

Tensile strength of AISI 4320 and 4320H nickel-chromium-molybdenum steels
versus Brinell hardness (3000-kgf applied load)

Table 3.14B. Statistical formula for calculating tensile strength: $\sigma = 496 \times \text{HB}$

Brinell hardness HB	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, pp.128, 129		σ_a / HB						
163	84000	515	80848	96.2	6,015	2,986,000	496	$\sigma = 496 \times \text{HB}$
201	102000	507	99696	97.7				
212	102000	481	105152	97.0				
235	115000	489	116560	98.7				
241	118000	490	119536	98.7				
248	120000	484	123008	97.6				
248	122000	492	123008	99.2				
255	130000	510	126480	97.3				
255	132000	518	126480	95.8				
293	146000	498	145328	99.5				
302	149000	493	149792	99.5				
302	152000	503	149792	98.5				
331	161000	486	164176	98.1				
341	167000	490	169136	98.7				
352	171000	486	174592	97.9				
375	180000	480	186000	96.8				
388	188000	485	192448	97.7				
415	212000	511	205840	97.1				
429	217000	506	212784	98.1				
429	218000	508	212784	97.6				

Linear regression formula for calculating tensile strength is on previous page

As can be seen from Tables 3.14A and 3.14B:

Linear regression formula provides 95.8 to 99.6% accuracy in calculating tensile strength

Statistical formula provides 95.8 to 99.5% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 160 to 430 HB

Appendix 3

Tensile strength of AISI 4340, 4340H, E4340, and E4340H nickel-chromium-molybdenum steels
versus Brinell hardness (3000-kgf applied load)

Table 3.15A. Linear regression formula for calculating tensile strength: $\sigma = 515 \times \text{HB} - 4322$

Brinell hardness HB	Tensile strength, psi		Accuracy in calcu- lating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, p.132									
217	108000	107433	99.5	23436000	47089	1.166E+10	515	-4322	0.9974
255	124000	127003	97.6	31620000	65025	1.538E+10			
269	134000	134213	99.8	36046000	72361	1.796E+10			
269	135000	134213	99.4	36315000	72361	1.823E+10			
277	139000	138333	99.5	38503000	76729	1.932E+10			
285	145000	142453	98.2	41325000	81225	2.103E+10			
293	147000	146573	99.7	43071000	85849	2.161E+10			
321	161000	160993	100	51681000	103041	2.592E+10			
331	165000	166143	99.3	54615000	109561	2.723E+10			
331	166000	166143	99.9	54946000	109561	2.756E+10			
341	170000	171293	99.2	57970000	116281	2.89E+10			
352	175000	176958	98.9	61600000	123904	3.063E+10			
363	182000	182623	99.7	66066000	131769	3.312E+10			
363	186000	182623	98.2	67518000	131769	3.46E+10			
4,267	2,137,000			664712000	1326525	3.331E+11			

Table 3.15B. Statistical formula for calculating tensile strength: $\sigma = 501 \times \text{HB}$

Brinell hardness HB	Tensile strength σ_a , psi	Strength-to- hardness ratio	Tensile strength calculated by the above formula	Accuracy in calcu- lating σ %	Cumulative values:		Average strength-to- hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, p.132		σ_a / HB	σ , psi					
217	108000	498	108717	99.3	4,267	2,137,000	501	$\sigma = 501 \times \text{HB}$
255	124000	486	127755	97.1				
269	134000	498	134769	99.4				
269	135000	502	134769	99.8				
277	139000	502	138777	99.8				
285	145000	509	142785	98.5				
293	147000	502	146793	99.9				
321	161000	502	160821	99.9				
331	165000	498	165831	99.5				
331	166000	502	165831	99.9				
341	170000	499	170841	99.5				
352	175000	497	176352	99.2				
363	182000	501	181863	99.9				
363	186000	512	181863	97.8				

As can be seen from Tables 3.15A and 3.15B:

Linear regression formula provides 97.6 to 100% accuracy in calculating tensile strength

Statistical formula provides 97.1 to 99.9% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 215 to 365 HB

Appendix 3

Tensile strength of AISI 4718 and 4718H nickel-chromium-molybdenum steels
versus Brinell hardness (3000-kgf applied load)

Table 3.16A. Linear regression formula for calculating tensile strength: $\sigma = 558 \times \text{HB} - 26000$

Brinell hardness HB	Tensile strength, psi		Accuracy in calcu- lating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, p.146									
321	154900	153118	98.8	49722900	103041	2.399E+10	558	-26000	0.9936
331	158900	158698	99.9	52595900	109561	2.525E+10			
331	159000	158698	99.8	52629000	109561	2.528E+10			
341	163500	164278	99.5	55753500	116281	2.673E+10			
341	164000	164278	99.8	55924000	116281	2.69E+10			
352	168100	170416	98.6	59171200	123904	2.826E+10			
352	170000	170416	99.8	59840000	123904	2.89E+10			
388	192000	190504	99.2	74496000	150544	3.686E+10			
2,757	1,330,400			460132500	953077	2.222E+11			

Table 3.16B. Statistical formula for calculating tensile strength: $\sigma = 483 \times \text{HB}$

Brinell hardness HB	Tensile strength σ_a , psi	Strength-to- hardness ratio σ_a / HB	Tensile strength calculated by the above formula σ , psi	Accuracy in calcu- lating σ %	Cumulative values:		Average strength-to- hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, p.146								
321	154900	483	155043	99.9	2,757	1,330,400	483	$\sigma = 483 \times \text{HB}$
331	158900	480	159873	99.4				
331	159000	480	159873	99.5				
341	163500	479	164703	99.3				
341	164000	481	164703	99.6				
352	168100	478	170016	98.9				
352	170000	483	170016	100				
388	192000	495	187404	97.6				

As can be seen from Tables 3.16A and 3.16B:

Linear regression formula provides 98.6 to 99.9% accuracy in calculating tensile strength

Statistical formula provides 97.6 to 100% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 320 to 390 HB

Appendix 3

Tensile strength of AISI 8620 and 8620H nickel-chromium-molybdenum steels
versus Brinell hardness (3000-kgf applied load)

Table 3.17A. Linear regression formula for calculating tensile strength: $\sigma = 494 \times \text{HB} + 189$

Brinell hardness HB	Tensile strength, psi		Accuracy in calcu- lating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, pp.190-192							494	189	0.9987
163	82000	80711	98.4	13366000	26569	6.724E+09			
179	87000	88615	98.2	15573000	32041	7.569E+09			
183	92000	90591	98.5	16836000	33489	8.464E+09			
197	96000	97507	98.5	18912000	38809	9.216E+09			
201	98000	99483	98.5	19698000	40401	9.604E+09			
229	114000	113315	99.4	26106000	52441	1.3E+10			
235	117000	116279	99.4	27495000	55225	1.369E+10			
248	124000	122701	99.0	30752000	61504	1.538E+10			
255	127000	126159	99.3	32385000	65025	1.613E+10			
262	130300	129617	99.5	34138600	68644	1.698E+10			
269	133000	133075	99.9	35777000	72361	1.769E+10			
321	156000	158763	98.3	50076000	103041	2.434E+10			
331	161000	163703	98.3	53291000	109561	2.592E+10			
341	167800	168643	99.5	57219800	116281	2.816E+10			
352	178000	174077	97.8	62656000	123904	3.168E+10			
388	192000	191861	99.9	74496000	150544	3.686E+10			
4,154	2,055,100			568777400	1149840	2.814E+11			

Table 3.17B. Statistical formula for calculating tensile strength: $\sigma = 495 \times \text{HB}$

Brinell hardness HB	Tensile strength σ_a , psi	Strength-to- hardness ratio	Tensile strength calculated by the above formula σ , psi	Accuracy in calcu- lating σ %	Cumulative values:		Average strength-to- hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, pp.190-192		σ_a / HB						
163	82000	503	80685	98.4	4,154	2,055,100	495	$\sigma = 495 \times \text{HB}$
179	87000	486	88605	98.2				
183	92000	503	90585	98.5				
197	96000	487	97515	98.4				
201	98000	488	99495	98.5				
229	114000	498	113355	99.4				
235	117000	498	116325	99.4				
248	124000	500	122760	99.0				
255	127000	498	126225	99.4				
262	130300	497	129690	99.5				
269	133000	494	133155	99.9				
321	156000	486	158895	98.2				
331	161000	486	163845	98.3				
341	167800	492	168795	99.4				
352	178000	506	174240	97.9				
388	192000	495	192060	100				

As can be seen from Tables 3.13A and 3.13B:

Linear regression formula provides 97.8 to 99.9% accuracy in calculating tensile strength

Statistical formula provides 97.9 to 100% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 160 to 390 HB

Appendix 3

Tensile strength of AISI 8630, 8630H, and 86B30H nickel-chromium-molybdenum steels
versus Brinell hardness (3000-kgf applied load)

Table 3.18A. Linear regression formula for calculating tensile strength: $\sigma = 501 \times \text{HB} - 1373$

Brinell hardness HB	Tensile strength, psi		Accuracy in calculating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, p.199							501	-1373	0.9948
187	92000	92314	99.7	17204000	34969	8.464E+09			
187	93000	92314	99.3	17391000	34969	8.649E+09			
187	94000	92314	98.2	17578000	34969	8.836E+09			
197	96000	97324	98.6	18912000	38809	9.216E+09			
217	107000	107344	99.7	23219000	47089	1.145E+10			
223	111000	110350	99.4	24753000	49729	1.232E+10			
235	113000	116362	97.1	26555000	55225	1.277E+10			
235	120000	116362	97.0	28200000	55225	1.44E+10			
241	118000	119368	98.9	28438000	58081	1.392E+10			
269	130000	133396	97.5	34970000	72361	1.69E+10			
269	134000	133396	99.5	36046000	72361	1.796E+10			
269	135000	133396	98.8	36315000	72361	1.823E+10			
285	139000	141412	98.3	39615000	81225	1.932E+10			
293	147000	145420	98.9	43071000	85849	2.161E+10			
302	152000	149929	98.6	45904000	91204	2.31E+10			
3,596	1,781,000			438171000	884426	2.171E+11			

Table 3.18B. Statistical formula for calculating tensile strength: $\sigma = 495 \times \text{HB}$

Brinell hardness HB	Tensile strength σ_a , psi	Strength-to-hardness ratio σ_a / HB	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, p.199					3,596	1,781,000	495	$\sigma = 495 \times \text{HB}$
187	92000	492	92565	99.4				
187	93000	497	92565	99.5				
187	94000	503	92565	98.5				
197	96000	487	97515	98.4				
217	107000	493	107415	99.6				
223	111000	498	110385	99.4				
235	113000	481	116325	97.1				
235	120000	511	116325	96.9				
241	118000	490	119295	98.9				
269	130000	483	133155	97.6				
269	134000	498	133155	99.4				
269	135000	502	133155	98.6				
285	139000	488	141075	98.5				
293	147000	502	145035	98.7				
302	152000	503	149490	98.3				

As can be seen from Tables 3.18A and 3.18B:

Linear regression formula provides 97.0 to 99.7% accuracy in calculating tensile strength

Statistical formula provides 97.1 to 99.6% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 185 to 305 HB

Appendix 3

Tensile strength of AISI 8640 and 8640H nickel-chromium-molybdenum steels
versus Brinell hardness (3000-kgf applied load)

Table 3.19A. Linear regression formula for calculating tensile strength: $\sigma = 454 \times \text{HB} + 11534$

Brinell hardness HB	Tensile strength, psi		Accuracy in calculating σ %	HB x σ_a	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, p.203							454	11534	0.9926
219	112000	110960	99.1	24528000	47961	1.254E+10			
277	137000	137292	<u>99.8</u>	37949000	76729	1.877E+10			
280	141000	138654	98.3	39480000	78400	1.988E+10			
283	137000	140016	<u>97.8</u>	38771000	80089	1.877E+10			
310	150000	152274	98.5	46500000	96100	2.25E+10			
342	169000	166802	98.7	57798000	116964	2.856E+10			
1,711	846,000			245026000	496243	1.21E+11			

Table 3.19B. Statistical formula for calculating tensile strength: $\sigma = 494 \times \text{HB}$

Brinell hardness HB	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, p.203		σ_a / HB	σ , psi	%				
219	112000	511	108186	<u>96.6</u>	1,711	846,000	494	$\sigma = 494 \times \text{HB}$
277	137000	495	136838	99.9				
280	141000	504	138320	98.1				
283	137000	484	139802	98.0				
310	150000	484	153140	97.9				
342	169000	494	168948	<u>100</u>				

As can be seen from Tables 3.19A and 3.19B:

Linear regression formula provides 97.8 to 99.8% accuracy in calculating tensile strength

Statistical formula provides 96.6 to 100% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 215 to 345 HB

Appendix 3

Tensile strength of AISI 8642 and 8642H nickel-chromium-molybdenum steels
versus Brinell hardness (3000-kgf applied load)

Table 3.20A. Linear regression formula for calculating tensile strength: $\sigma = 489 \times \text{HB} + 1737$

Brinell hardness HB	Tensile strength, psi		Accuracy in calculating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, p.206							489	1737	0.9988
235	117000	116652	99.7	27495000	55225	1.369E+10			
248	124000	123009	99.2	30752000	61504	1.538E+10			
262	130000	129855	99.9	34060000	68644	1.69E+10			
269	131000	133278	<u>98.3</u>	35239000	72361	1.716E+10			
277	138000	137190	99.4	38226000	76729	1.904E+10			
285	141000	141102	<u>99.9</u>	40185000	81225	1.988E+10			
306	151000	151371	99.8	46206000	93636	2.28E+10			
321	159000	158706	99.8	51039000	103041	2.528E+10			
331	163000	163596	99.6	53953000	109561	2.657E+10			
363	180000	179244	99.6	65340000	131769	3.24E+10			
2,897	1,434,000			422495000	853695	2.091E+11			

Table 3.20B. Statistical formula for calculating tensile strength: $\sigma = 494 \times \text{HB}$

Brinell hardness HB	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, p.206		σ_a / HB	σ , psi	%	2,897	1,434,000	495	$\sigma = 494 \times \text{HB}$
235	117000	498	116325	99.4				
248	124000	500	122760	99.0				
262	130000	496	129690	99.8				
269	131000	487	133155	<u>98.4</u>				
277	138000	498	137115	99.4				
285	141000	495	141075	<u>99.9</u>				
306	151000	493	151470	99.7				
321	159000	495	158895	<u>99.9</u>				
331	163000	492	163845	99.5				
363	180000	496	179685	99.8				

As can be seen from Tables 3.20A and 3.20B:

Linear regression formula provides 98.3 to 99.9% accuracy in calculating tensile strength

Statistical formula provides 98.4 to 99.95% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 235 to 365 HB

Appendix 3

Tensile strength of AISI 8650, 8650H, and 86B50 nickel-chromium-molybdenum steels
versus Brinell hardness (3000-kgf applied load)

Table 3.21A. Linear regression formula for calculating tensile strength: $\sigma = 488 \times \text{HB} + 1743$

Brinell hardness HB	Tensile strength, psi		Accuracy in calcu- lating σ %	HB x σ_a	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, pp.209, 210									
212	104000	105199	98.9	22048000	44944	1.082E+10	488	1743	0.9947
241	122000	119351	97.8	29402000	58081	1.488E+10			
255	126000	126183	<u>99.9</u>	32130000	65025	1.588E+10			
277	135000	136919	98.6	37395000	76729	1.823E+10			
285	139000	140823	98.7	39615000	81225	1.932E+10			
285	141000	140823	<u>99.9</u>	40185000	81225	1.988E+10			
285	143000	140823	98.5	40755000	81225	2.045E+10			
293	144000	144727	99.5	42192000	85849	2.074E+10			
293	145000	144727	99.8	42485000	85849	2.103E+10			
293	148000	144727	97.8	43364000	85849	2.19E+10			
302	148000	149119	99.2	44696000	91204	2.19E+10			
302	149000	149119	<u>99.9</u>	44998000	91204	2.22E+10			
311	154000	153511	99.7	47894000	96721	2.372E+10			
321	154000	158391	<u>97.2</u>	49434000	103041	2.372E+10			
331	165000	163271	99.0	54615000	109561	2.723E+10			
352	172000	173519	99.1	60544000	123904	2.958E+10			
363	178000	178887	99.5	64614000	131769	3.168E+10			
363	182000	178887	98.3	66066000	131769	3.312E+10			
5,364	2,649,000			802432000	1625174	3.963E+11			

Statistical formula for calculating tensile strength is on the next page

Appendix 3

Tensile strength of AISI 8650, 8650H, and 86B50 nickel-chromium-molybdenum steels
versus Brinell hardness (3000-kgf applied load)

Table 3.21B. Statistical formula for calculating tensile strength: $\sigma = 494 \times \text{HB}$

Brinell hardness HB	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, pp.209, 210		σ_a / HB						
212	104000	491	104728	99.3	5,364	2,649,000	494	$\sigma = 494 \times \text{HB}$
241	122000	506	119054	97.6				
255	126000	494	125970	100				
277	135000	487	136838	98.7				
285	139000	488	140790	98.7				
285	141000	495	140790	99.9				
285	143000	502	140790	98.5				
293	144000	491	144742	99.5				
293	145000	495	144742	99.8				
293	148000	505	144742	97.8				
302	148000	490	149188	99.2				
302	149000	493	149188	99.9				
311	154000	495	153634	99.8				
321	154000	480	158574	97.1				
331	165000	498	163514	99.1				
352	172000	489	173888	98.9				
363	178000	490	179322	99.3				
363	182000	501	179322	98.5				

Linear regression formula for calculating tensile strength is on previous page

As can be seen from Tables 3.21A and 3.21B:

Linear regression formula provides 97.2 to 99.9% accuracy in calculating tensile strength

Statistical formula provides 97.1 to 100% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 210 to 365 HB

Appendix 3

Tensile strength of AISI 8740 and 8740H nickel-chromium-molybdenum steels
versus Brinell hardness (3000-kgf applied load)

Table 3.22A. Linear regression formula for calculating tensile strength: $\sigma = 514 \times \text{HB} - 3411$

Brinell hardness HB	Tensile strength, psi		Accuracy in calculating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, p.218							514	-3411	0.9937
201	101000	99903	98.9	20301000	40401	1.02E+10			
229	116000	114295	98.5	26564000	52441	1.346E+10			
248	124000	124061	<u>100</u>	30752000	61504	1.538E+10			
255	127000	127659	99.5	32385000	65025	1.613E+10			
262	132000	131257	99.4	34584000	68644	1.742E+10			
269	135000	134855	99.9	36315000	72361	1.823E+10			
269	136000	134855	99.2	36584000	72361	1.85E+10			
277	139000	138967	<u>100</u>	38503000	76729	1.932E+10			
277	142000	138967	97.9	39334000	76729	2.016E+10			
285	138000	143079	96.5	39330000	81225	1.904E+10			
285	140000	143079	97.8	39900000	81225	1.96E+10			
302	149000	151817	98.1	44998000	91204	2.22E+10			
311	154000	156443	98.4	47894000	96721	2.372E+10			
331	171000	166723	<u>97.5</u>	56601000	109561	2.924E+10			
352	178000	177517	99.7	62656000	123904	3.168E+10			
352	179000	177517	99.2	63008000	123904	3.204E+10			
4,505	2,261,000			649709000	1293939	3.263E+11			

Table 3.22B. Statistical formula for calculating tensile strength: $\sigma = 502 \times \text{HB}$

Brinell hardness HB	Tensile strength σ_a , psi	Strength-to-hardness ratio σ_a / HB	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, p.218					4,505	2,261,000	502	$\sigma = 502 \times \text{HB}$
201	101000	502	100902	99.9				
229	116000	507	114958	99.1				
248	124000	500	124496	99.6				
255	127000	498	128010	99.2				
262	132000	504	131524	99.6				
269	135000	502	135038	<u>100</u>				
269	136000	506	135038	99.3				
277	139000	502	139054	<u>100</u>				
277	142000	513	139054	97.9				
285	138000	484	143070	96.5				
285	140000	491	143070	97.9				
302	149000	493	151604	98.3				
311	154000	495	156122	98.6				
331	171000	517	166162	<u>97.2</u>				
352	178000	506	176704	99.3				
352	179000	509	176704	98.7				

As can be seen from Tables 3.22A and 3.22B:

Linear regression formula provides 97.5 to 100% accuracy in calculating tensile strength

Statistical formula provides 97.2 to 100% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 200 to 355 HB

Appendix 3

Tensile strength of AISI E9310 and E9310H nickel-chromium-molybdenum steels
versus Brinell hardness (3000-kgf applied load)

Table 3.23A. Linear regression formula for calculating tensile strength: $\sigma = 479 \times \text{HB} + 3465$

Brinell hardness HB	Tensile strength, psi		Accuracy in calcu- lating σ %	HB x σ_a	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, pp.224-226							479	3465	0.9956
241	119000	118904	99.9	28679000	58081	1.416E+10			
255	125000	125610	99.5	31875000	65025	1.563E+10			
262	131000	128963	98.4	34322000	68644	1.716E+10			
269	132000	132316	99.8	35508000	72361	1.742E+10			
277	136000	136148	99.9	37672000	76729	1.85E+10			
293	144000	143812	99.9	42192000	85849	2.074E+10			
293	145000	143812	99.2	42485000	85849	2.103E+10			
302	145000	148123	97.9	43790000	91204	2.103E+10			
321	158000	157224	99.5	50718000	103041	2.496E+10			
321	159000	157224	98.9	51039000	103041	2.528E+10			
341	164000	166804	98.3	55924000	116281	2.69E+10			
341	168000	166804	99.3	57288000	116281	2.822E+10			
352	169500	172073	98.5	59664000	123904	2.873E+10			
352	171000	172073	99.4	60192000	123904	2.924E+10			
363	174500	177342	98.4	63343500	131769	3.045E+10			
363	178000	177342	99.6	64614000	131769	3.168E+10			
363	179000	177342	99.1	64977000	131769	3.204E+10			
375	187000	183090	97.9	70125000	140625	3.497E+10			
5,684	2,785,000			894407500	1826126	4.381E+11			

Statistical formula for calculating tensile strength is on the next page

Appendix 3

Tensile strength of AISI E9310 and E9310H nickel-chromium-molybdenum steels
versus Brinell hardness (3000-kgf applied load)

Table 3.23B. Statistical formula for calculating tensile strength: $\sigma = 490 \times \text{HB}$

Brinell hardness HB	Tensile strength σ_a , psi	Strength-to-hardness ratio σ_a / HB	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, pp.224-226					5,684	2,785,000	490	$\sigma = 490 \times \text{HB}$
241	119000	494	118090	99.2				
255	125000	490	124950	100				
262	131000	500	128380	98.0				
269	132000	491	131810	99.9				
277	136000	491	135730	99.8				
293	144000	491	143570	99.7				
293	145000	495	143570	99.0				
302	145000	480	143570	99.0				
321	158000	492	157290	99.6				
321	159000	495	157290	98.9				
341	164000	481	167090	98.2				
341	168000	493	167090	99.5				
352	169500	482	172480	98.3				
352	171000	486	172480	99.1				
363	174500	481	177870	98.1				
363	178000	490	177870	99.9				
363	179000	493	177870	99.4				
375	187000	499	183750	98.3				

Linear regression formula for calculating tensile strength is on previous page

As can be seen from Tables 3.23A and 3.23B:

Linear regression formula provides 97.9 to 99.9% accuracy in calculating tensile strength

Statistical formula provides 98.0 to 100% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 240 to 375 HB

Appendix 3

Tensile strength of AISI 9840 nickel-chromium-molybdenum steel after quenching in oil
versus Brinell hardness (3000-kgf applied load)

Table 3.24A. Linear regression formula for calculating tensile strength: $\sigma = 494 \times \text{HB} + 1591$

Brinell hardness HB	Tensile strength, psi		Accuracy in calculating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, p.233									
280	140000	139911	99.9	39200000	78400	1.96E+10	494	1591	0.99997
321	160000	160165	99.9	51360000	103041	2.56E+10			
361	180000	179925	100	64980000	130321	3.24E+10			
962	480,000			155540000	311762	7.76E+10			

Table 3.24B. Statistical formula for calculating tensile strength: $\sigma = 499 \times \text{HB}$

Brinell hardness HB	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, p.233		σ_a / HB						
280	140000	500	139720	99.8	962	480,000	499	$\sigma = 499 \times \text{HB}$
321	160000	498	160179	99.9				
361	180000	499	180139	99.9				

As can be seen from Tables 3.24A and 3.24B:

Linear regression formula provides 99.9 to 100% accuracy in calculating tensile strength

Statistical formula provides 99.8 to 99.9% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 280 to 365 HB

Appendix 3

Tensile strength of AISI 9255 silicon-manganese steel versus Brinell hardness (3000-kgf load)

Table 3.25A. Linear regression formula for calculating tensile strength: $\sigma = 567 \times \text{HB} - 17800$

Brinell hardness HB	Tensile strength, psi		Accuracy in calculating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref. 8, pp.220, 221							567	-17800	0.9965
229	112000	112043	<u>100</u>	25648000	52441	1.254E+10			
229	113000	112043	99.2	25877000	52441	1.277E+10			
262	132000	130754	99.1	34584000	68644	1.742E+10			
269	133000	134723	98.7	35777000	72361	1.769E+10			
269	135000	134723	99.8	36315000	72361	1.823E+10			
277	137000	139259	<u>98.4</u>	37949000	76729	1.877E+10			
277	138000	139259	99.1	38226000	76729	1.904E+10			
285	145000	143795	99.2	41325000	81225	2.103E+10			
293	146000	148331	<u>98.4</u>	42778000	85849	2.132E+10			
293	149000	148331	99.6	43657000	85849	2.22E+10			
293	150000	148331	98.9	43950000	85849	2.25E+10			
302	155000	153434	99.0	46810000	91204	2.403E+10			
321	164000	164207	99.9	52644000	103041	2.69E+10			
331	170000	169877	99.9	56270000	109561	2.89E+10			
3,930	1,979,000			561810000	1114284	2.833E+11			

Table 3.25B. Statistical formula for calculating tensile strength: $\sigma = 504 \times \text{HB}$

Brinell hardness HB	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref. 8, pp.220, 221		σ_a / HB	σ , psi	%				
229	112000	489	115416	<u>97.0</u>	3,930	1,979,000	504	$\sigma = 504 \times \text{HB}$
229	113000	493	115416	97.9				
262	132000	504	132048	<u>100</u>				
269	133000	494	135576	98.1				
269	135000	502	135576	99.6				
277	137000	495	139608	98.1				
277	138000	498	139608	98.8				
285	145000	509	143640	99.1				
293	146000	498	147672	98.9				
293	149000	509	147672	99.1				
293	150000	512	147672	98.4				
302	155000	513	152208	98.2				
321	164000	511	161784	98.6				
331	170000	514	166824	98.1				

As can be seen from Tables 3.25A and 3.25B:

Linear regression formula provides 98.4 to 100% accuracy in calculating tensile strength

Statistical formula provides 97.0 to 100% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 225 to 335 HB

APPENDIX 4. STAINLESS STEELS

TENSILE STRENGTH versus BRINELL HARDNESS

Tables 4.1A and 4.1B. AISI type 201 austenitic chromium-nickel-manganese steel
Tables 4.2A and 4.2B. AISI type 301 austenitic chromium-nickel steel
Tables 4.3A and 4.3B. AISI types 302 and 302B austenitic chromium-nickel steels
Tables 4.4A and 4.4B. AISI types 304, 304N, and 304HN austenitic chromium-nickel steels
Tables 4.5A and 4.5B. AISI type 308 austenitic high-chromium, high-nickel steel
Tables 4.6A and 4.6B. AISI types 316, 316L, 316F, and 316N austenitic, chromium-nickel-molybdenum steels
Tables 4.7A and 4.7B. AISI type 321 austenitic, titanium-bearing, chromium-nickel steel
Tables 4.8A and 4.8B. AISI types 347 and 348 austenitic chromium-nickel steels
Tables 4.9A and 4.9B. AISI type 403 martensitic chromium steel
Tables 4.10A and 4.10B. AISI type 414 martensitic chromium-nickel steel
Tables 4.11A and 4.11B. AISI types 416 and 416Se martensitic chromium steels
Tables 4.12A and 4.12B. AISI types 420 and 420F martensitic chromium steels
Tables 4.13A and 4.13B. AISI type 431 martensitic chromium-nickel steel
Tables 4.14A and 4.14B. AISI type 440A martensitic high-chromium steel
Tables 4.15A and 4.15B. AISI type 440B martensitic high-chromium steel
Tables 4.16A and 4.16B. AISI type 440C martensitic high-chromium steel
Tables 4.17A and 4.17B. AISI type 405 ferritic chromium steel
Tables 4.18A and 4.18B. AISI types 430, 434, and 436 ferritic chromium steels
Tables 4.19A and 4.19B. AISI type 446 ferritic high-chromium steel
Tables 4.20A and 4.20B. UNS S13800 (PH 13-8) precipitation-hardening, chromium-nickel steel
Tables 4.21A and 4.21B. UNS S15500 (15-5 PH) martensitic, precipitation-hardening steel
Tables 4.22A and 4.22B. AISI type 630, UNS S17400 (17-4 PH) precipitation-hardening steel
Tables 4.23A and 4.23B. AISI type 631, UNS S17700 (17-7 PH) precipitation-hardening steel
Tables 4.24A and 4.24B. UNS S45000 (Custom 450) martensitic precipitation-hardening steel
Tables 4.25A and 4.25B. UNS S45500 (Custom 455) martensitic precipitation-hardening steel

Appendix 4

Tensile strength of AISI Type 201 austenitic chromium-nickel-manganese stainless steel
versus Brinell hardness (3000-kgf applied load)

Table 4.1A. Linear regression formula for calculating tensile strength: $\sigma = 606 \times \text{HB} - 31737$

Brinell hardness HB*	Tensile strength, psi		Accuracy in calculating σ %	HB x σ_a	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, p.247							606	-31737	0.9637
253	125000	121581	97.3	31625000	64009	1.563E+10			
302	150000	151275	<u>99.2</u>	45300000	91204	2.25E+10			
344	175000	176727	99.0	60200000	118336	3.063E+10			
381	185000	199149	<u>92.9</u>	70485000	145161	3.423E+10			
401	225000	211269	93.9	90225000	160801	5.063E+10			
1,681	860,000			297835000	579511	1.536E+11			

Table 4.1B. Statistical formula for calculating tensile strength: $\sigma = 512 \times \text{HB}$

Brinell hardness HB*	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, p.247		σ_a / HB						
253	125000	494	129536	96.5	1,681	860,000	512	$\sigma = 512 \times \text{HB}$
302	150000	497	154624	97.0				
344	175000	509	176128	<u>99.4</u>				
381	185000	486	195072	94.8				
401	225000	561	205312	<u>91.2</u>				

* **Notice:** Brinell hardness numbers (HB) were obtained by converting Rockwell hardness numbers (HRC) provided.

As can be seen from Tables 4.1A and 4.1B:

Linear regression formula provides 92.9 to 99.2% accuracy in calculating tensile strength

Statistical formula provides 91.2 to 99.4% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 250 to 405 HB

Appendix 4

Tensile strength of AISI Type 301 austenitic chromium-nickel stainless steel
versus Brinell hardness (3000-kgf applied load)

Table 4.2A. Linear regression formula for calculating tensile strength: $\sigma = 609 \times \text{HB} - 27508$

Brinell hardness HB*	Tensile strength, psi		Accuracy in calculating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, p.255									
253	125000	126569	<u>98.8</u>	31625000	64009	1.563E+10	609	-27508	0.9756
286	150000	146666	97.8	42900000	81796	2.25E+10			
327	175000	171635	98.1	57225000	106929	3.063E+10			
371	185000	198431	<u>93.2</u>	68635000	137641	3.423E+10			
401	225000	216701	96.3	90225000	160801	5.063E+10			
1,638	860,000			290610000	551176	1.536E+11			

Table 4.2B. Statistical formula for calculating tensile strength: $\sigma = 525 \times \text{HB}$

Brinell hardness HB*	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, p.255		σ_a / HB						
253	125000	494	132825	94.1	1,638	860,000	525	$\sigma = 525 \times \text{HB}$
286	150000	524	150150	<u>99.9</u>				
327	175000	535	171675	98.1				
371	185000	499	194775	95.0				
401	225000	561	210525	<u>93.6</u>				

* Notice: Brinell hardness numbers (HB) were obtained by converting Rockwell hardness numbers (HRC) provided.

As can be seen from Tables 4.2A and 4.2B:

Linear regression formula provides 93.2 to 98.8% accuracy in calculating tensile strength

Statistical formula provides 93.6 to 99.9% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 250 to 405 HB

Appendix 4

Tensile strength of AISI Types 302 and 302B austenitic chromium-nickel stainless steels
versus Brinell hardness (3000-kgf applied load)

Table 4.3A. Linear regression formula for calculating tensile strength: $\sigma = 353 \times \text{HB} + 35507$

Brinell hardness HB*	Tensile strength, psi		Accuracy in calculating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, pp.259, 262									
146	85000	87045	97.7	12410000	21316	7.225E+09	353	35507	0.9873
146	90000	87045	<u>96.7</u>	13140000	21316	8.1E+09			
163	90000	93046	<u>96.7</u>	14670000	26569	8.1E+09			
163	95000	93046	97.9	15485000	26569	9.025E+09			
253	125000	124816	<u>99.9</u>	31625000	64009	1.563E+10			
871	485,000			87330000	159779	4.808E+10			

Table 4.3B. Statistical formula for calculating tensile strength: $\sigma = 557 \times \text{HB}$

Brinell hardness HB*	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, pp.259, 262		σ_a / HB						
146	85000	582	81322	95.7	871	485,000	557	$\sigma = 557 \times \text{HB}$
146	90000	616	81322	90.4				
163	90000	552	90791	<u>99.1</u>				
163	95000	583	90791	95.6				
253	125000	494	140921	<u>88.7</u>				

* Notice: Brinell hardness numbers (HB) were obtained by converting Rockwell hardness numbers (HRB and HRC) provided.

As can be seen from Tables 4.3A and 4.3B:

Linear regression formula provides 96.7 to 99.9% accuracy in calculating tensile strength

Statistical formula provides 88.7 to 99.1% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 145 to 255 HB

Appendix 4

Tensile strength of AISI Types 304, 304N, and 304HN austenitic chromium-nickel stainless steels
versus Brinell hardness (3000-kgf applied load)

Table 4.4A. Linear regression formula for calculating tensile strength: $\sigma = 325 \times \text{HB} + 35246$

Brinell hardness HB*	Tensile strength, psi		Accuracy in calculating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, pp.274, 281							325	35246	0.9842
<u>146</u>	84000	82696	98.4	12264000	21316	7.056E+09			
149	82000	83671	98.0	12218000	22201	6.724E+09			
149	85000	83671	98.4	12665000	22201	7.225E+09			
<u>156</u>	90000	85946	<u>95.5</u>	14040000	24336	8.1E+09			
<u>163</u>	90000	88221	98.0	14670000	26569	8.1E+09			
180	90000	93746	96.0	16200000	32400	8.1E+09			
<u>203</u>	105000	101221	96.4	21315000	41209	1.103E+10			
<u>209</u>	100000	103171	96.9	20900000	43681	1E+10			
212	100000	104146	96.0	21200000	44944	1E+10			
240	110000	113246	97.1	26400000	57600	1.21E+10			
277	125000	125271	<u>99.8</u>	34625000	76729	1.563E+10			
<u>310</u>	140000	135996	97.1	43400000	96100	1.96E+10			
2,394	1,201,000			249897000	509286	1.237E+11			

Table 4.4B. Statistical formula for calculating tensile strength: $\sigma = 502 \times \text{HB}$

Brinell hardness HB*	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, pp.274, 281		σ_a / HB			HB			
<u>146</u>	84000	575	73292	87.3	2,394	1,201,000	502	$\sigma = 502 \times \text{HB}$
149	82000	550	74798	91.2				
149	85000	570	74798	88.0				
<u>156</u>	90000	577	78312	<u>87.0</u>				
<u>163</u>	90000	552	81826	90.9				
180	90000	500	90360	<u>99.6</u>				
<u>203</u>	105000	517	101906	97.1				
<u>209</u>	100000	478	104918	95.3				
212	100000	472	106424	94.0				
240	110000	458	120480	91.3				
277	125000	451	139054	89.9				
<u>310</u>	140000	452	155620	90.0				

* Notice: Underlined Brinell hardness numbers (HB) were obtained by converting Rockwell hardness numbers (HRB and HRC) provided.

As can be seen from Tables 4.4A and 4.4B:

Linear regression formula provides 95.5 to 99.8% accuracy in calculating tensile strength

Statistical formula provides 87.0 to 99.6% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 145 to 310 HB

Appendix 4

Tensile strength of AISI Type 308 austenitic high-chromium, high-nickel stainless steel
versus Brinell hardness (3000-kgf applied load)

Table 4.5A. Linear regression formula for calculating tensile strength: $\sigma = 695 \times \text{HB} - 61198$

Brinell hardness HB*	Tensile strength, psi		Accuracy in calcu- lating σ %	HB x σ_a	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, p.284							695	-61198	0.9920
242	110000	106992	97.3	26620000	58564	1.21E+10			
272	130000	127842	98.3	35360000	73984	1.69E+10			
279	130000	132707	98.0	36270000	77841	1.69E+10			
302	150000	148692	<u>99.1</u>	45300000	91204	2.25E+10			
310	150000	154252	97.2	46500000	96100	2.25E+10			
344	170000	177882	<u>95.6</u>	58480000	118336	2.89E+10			
353	190000	184137	96.9	67070000	124609	3.61E+10			
401	220000	217497	98.9	88220000	160801	4.84E+10			
2,503	1,250,000			403820000	801439	2.043E+11			

Table 4.5B. Statistical formula for calculating tensile strength: $\sigma = 499 \times \text{HB}$

Brinell hardness HB*	Tensile strength σ _a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula	Accuracy in calculating σ	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ, psi		
Ref 8, p.284		σ _a / HB	σ, psi	%	HB	σ, psi		
242	110000	455	120758	91.1	2,503	1,250,000	499	σ = 499 x HB
272	130000	478	135728	95.8				
279	130000	466	139221	93.4				
302	150000	497	150698	<u>99.5</u>				
310	150000	484	154690	97.0				
344	170000	494	171656	99.0				
353	190000	538	176147	92.7				
401	220000	549	200099	<u>91.0</u>				

* Notice: Brinell hardness numbers (HB) were obtained
by converting Rockwell hardness numbers (HRC) provided.

As can be seen from Tables 4.5A and 4.5B:

Linear regression formula provides 95.6 to 99.1% accuracy in calculating tensile strength

Statistical formula provides 91.0 to 99.5% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 240 to 405 HB

Appendix 4

Tensile strength of AISI Types 316, 316L, 316F, and 316N austenitic chromium-nickel-molybdenum stainless steels
versus Brinell hardness (3000-kgf applied load)

Table 4.6A. Linear regression formula for calculating tensile strength: $\sigma = 231 \times \text{HB} + 47879$

Brinell hardness HB*	Tensile strength, psi		Accuracy in calculating σ %	HB x σ_a	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, p.293,-7,-9, 300							231	47879	0.9030
<u>141</u>	80000	80450	99.4	11280000	19881	6.4E+09			
143	82000	80912	98.7	11726000	20449	6.724E+09			
<u>144</u>	81000	81143	<u>99.8</u>	11664000	20736	6.561E+09			
146	81000	81605	99.3	11826000	21316	6.561E+09			
149	80000	82298	97.2	11920000	22201	6.4E+09			
149	82000	82298	99.6	12218000	22201	6.724E+09			
<u>163</u>	85000	85532	99.4	13855000	26569	7.225E+09			
<u>163</u>	90000	85532	<u>95.0</u>	14670000	26569	8.1E+09			
180	90000	89459	99.4	16200000	32400	8.1E+09			
190	90000	91769	98.1	17100000	36100	8.1E+09			
1,568	841,000			132459000	248422	7.09E+10			

Table 4.6B. Statistical formula for calculating tensile strength: $\sigma = 536 \times \text{HB}$

Brinell hardness HB*	Tensile strength σ_a , psi	Strength-to- hardness ratio	Tensile strength calculated by the above formula	Accuracy in calculating σ %	Cumulative values:		Average strength-to- hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, p.293,-7,-9, 300		σ_a / HB	σ , psi	%	HB	σ , psi	ratio σ / HB	
<u>141</u>	80000	567	75576	94.5	1,568	841,000	536	$\sigma = 536 \times \text{HB}$
143	82000	573	76648	93.5				
<u>144</u>	81000	563	77184	95.3				
146	81000	555	78256	96.6				
149	80000	537	79864	<u>99.8</u>				
149	82000	550	79864	97.4				
<u>163</u>	85000	521	87368	97.3				
<u>163</u>	90000	552	87368	97.1				
180	90000	500	96480	93.3				
190	90000	474	101840	<u>88.4</u>				

* Notice: Underlined Brinell hardness numbers (HB) were obtained
by converting Rockwell hardness numbers (HRB) provided.

As can be seen from Tables 4.6A and 4.6B:

Linear regression formula provides 95.0 to 99.8% accuracy in calculating tensile strength

Statistical formula provides 88.4 to 99.8% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 140 to 190 HB

Appendix 4

Tensile strength of AISI Type 321 austenitic titanium-bearing, chromium-nickel stainless steel
versus Brinell hardness (3000-kgf applied load)

Table 4.7A. Linear regression formula for calculating tensile strength: $\sigma = 339 \times \text{HB} + 32879$

Brinell hardness HB*	Tensile strength, psi		Accuracy in calculating σ %	HB x σ_a	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, p.305									
150	85000	83729	98.5	12750000	22500	7.225E+09	339	32879	0.9564
160	85000	87119	<u>97.6</u>	13600000	25600	7.225E+09			
<u>179</u>	95000	93560	98.5	17005000	32041	9.025E+09			
185	95000	95594	<u>99.4</u>	17575000	34225	9.025E+09			
674	360000			60930000	114366	3.25E+10			

Table 4.7B. Statistical formula for calculating tensile strength: $\sigma = 534 \times \text{HB}$

Brinell hardness HB*	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, p.305		σ_a / HB						
150	85000	567	80100	<u>94.2</u>	674	360,000	534	$\sigma = 534 \times \text{HB}$
160	85000	531	85440	<u>99.5</u>				
<u>179</u>	95000	531	95586	99.4				
185	95000	514	98790	96.2				

* Notice: Underlined Brinell hardness number (HB) was obtained by converting Rockwell hardness number (HRB) provided.

As can be seen from Tables 4.7A and 4.7B:

Linear regression formula provides 97.6 to 99.4% accuracy in calculating tensile strength

Statistical formula provides 94.2 to 99.5% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 150 to 185 HB

Appendix 4

Tensile strength of AISI Types 347 and 348 austenitic chromium-nickel stainless steels
versus Brinell hardness (3000-kgf applied load)

Table 4.8A. Linear regression formula for calculating tensile strength: $\sigma = 156 \times \text{HB} + 67234$

Brinell hardness HB*	Tensile strength, psi		Accuracy in calculating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, p.312									
160	90000	92194	97.6	14400000	25600	8.1E+09	156	67234	0.9213
<u>163</u>	95000	92662	<u>97.5</u>	15485000	26569	9.025E+09			
<u>209</u>	100000	99838	<u>99.8</u>	20900000	43681	1E+10			
212	100000	100306	99.7	21200000	44944	1E+10			
744	385,000			71985000	140794	3.713E+10			

Table 4.8B. Statistical formula for calculating tensile strength: $\sigma = 517 \times \text{HB}$

Brinell hardness HB*	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, p.312		σ_a / HB						
160	90000	563	82720	91.9	744	385,000	517	$\sigma = 517 \times \text{HB}$
<u>163</u>	95000	583	84271	<u>88.7</u>				
<u>209</u>	100000	478	108053	<u>92.5</u>				
212	100000	472	109604	91.2				

* Notice: Underlined Brinell hardness numbers (HB) were obtained by converting Rockwell hardness numbers (HRB) provided.

As can be seen from Tables 4.8A and 4.8B:

Linear regression formula provides 97.5 to 99.8% accuracy in calculating tensile strength

Statistical formula provides 88.7 to 92.5% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 160 to 215 HB

Appendix 4

Tensile strength of AISI Type 403 martensitic chromium stainless steel
versus Brinell hardness (3000-kgf applied load)

Table 4.9A. Linear regression formula for calculating tensile strength: $\sigma = 536 \times \text{HB} - 7792$

Brinell hardness HB*	Tensile strength, psi		Accuracy in calculating σ %	HB x σ_a	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, p.318									
146	70000	70464	99.3	10220000	21316	4.9E+09	536	-7792	0.9994
153	75000	74216	99.0	11475000	23409	5.625E+09			
193	95000	95656	99.3	18335000	37249	9.025E+09			
221	111000	110664	99.7	24531000	48841	1.232E+10			
713	351,000			64561000	130815	3.187E+10			

Table 4.9B. Statistical formula for calculating tensile strength: $\sigma = 492 \times \text{HB}$

Brinell hardness HB*	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, p.318		σ_a / HB	σ , psi	%				
146	70000	479	71832	97.4	713	351,000	492	$\sigma = 492 \times \text{HB}$
153	75000	490	75276	99.6				
193	95000	492	94956	100				
221	111000	502	108732	98.0				

* Notice: Brinell hardness numbers (HB) were obtained
by converting Rockwell hardness numbers (HRB) provided.

As can be seen from Tables 4.9A and 4.9B:

Linear regression formula provides 99.0 to 99.7% accuracy in calculating tensile strength

Statistical formula provides 97.4 to 100% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 145 to 225 HB

Appendix 4

Tensile strength of AISI Type 414 martensitic chromium-nickel stainless steel
versus Brinell hardness (3000-kgf applied load)

Table 4.10A. Linear regression formula for calculating tensile strength: $\sigma = 513 \times \text{HB} - 4350$

Brinell hardness HB*	Tensile strength, psi		Accuracy in calculating σ %	HB x σ_a	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref. 8, pp.332, 333							513	-4350	0.9952
<u>228</u>	120000	112614	<u>93.8</u>	27360000	51984	1.44E+10			
235	115000	116205	99.0	27025000	55225	1.323E+10			
270	130000	134160	96.9	35100000	72900	1.69E+10			
<u>279</u>	135000	138777	97.3	37665000	77841	1.823E+10			
<u>416</u>	207500	209058	<u>99.3</u>	86320000	173056	4.306E+10			
<u>426</u>	217500	214188	98.5	92655000	181476	4.731E+10			
1,854	925,000			306125000	612482	1.531E+11			

Table 4.10B. Statistical formula for calculating tensile strength: $\sigma = 499 \times \text{HB}$

Brinell hardness HB*	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref. 8, p.333		σ_a / HB						
<u>228</u>	120000	526	113772	<u>94.8</u>	1,854	925,000	499	$\sigma = 499 \times \text{HB}$
235	115000	489	117265	98.1				
270	130000	481	134730	96.5				
<u>279</u>	135000	484	139221	97.0				
<u>416</u>	207500	499	207584	<u>100</u>				
<u>426</u>	217500	511	212574	97.7				

* **Notice:** Underlined Brinell hardness numbers (HB) were obtained by converting Rockwell hardness numbers (HRB and HRC) provided.

As can be seen from Tables 4.10A and 4.10B:

Linear regression formula provides 93.8 to 99.3% accuracy in calculating tensile strength

Statistical formula provides 94.8 to 100% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 225 to 430 HB

Appendix 4

Tensile strength of AISI Types 416 and 416Se martensitic chromium stainless steels
versus Brinell hardness (3000-kgf applied load)

Table 4.11A. Linear regression formula for calculating tensile strength: $\sigma = 527 \times \text{HB} - 9448$

Brinell hardness HB*	Tensile strength, psi		Accuracy in calculating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, pp.338, 339							527	-9448	0.9936
153	75000	71183	<u>94.9</u>	11475000	23409	5.625E+09			
193	90000	92263	97.5	17370000	37249	8.1E+09			
203	100000	97533	97.5	20300000	41209	1E+10			
221	110000	107019	97.3	24310000	48841	1.21E+10			
226	107500	109654	98.0	24295000	51076	1.156E+10			
245	115500	119667	96.5	28297500	60025	1.334E+10			
258	125500	126518	99.2	32379000	66564	1.575E+10			
279	135000	137585	98.1	37665000	77841	1.823E+10			
319	157000	158665	99.0	50083000	101761	2.465E+10			
362	172000	181326	<u>94.9</u>	62264000	131044	2.958E+10			
362	182500	181326	<u>99.4</u>	66065000	131044	3.331E+10			
362	187500	181326	96.7	67875000	131044	3.516E+10			
366	190000	183434	96.5	69540000	133956	3.61E+10			
3,549	1,747,500			511918500	1035063	2.535E+11			

Table 4.11B. Statistical formula for calculating tensile strength: $\sigma = 492 \times \text{HB}$

Brinell hardness HB*	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, pp.338, 339		σ_a / HB			HB			
153	75000	490	75276	99.6	3,549	1,747,500	492	$\sigma = 492 \times \text{HB}$
193	90000	466	94956	<u>94.8</u>				
203	100000	493	99876	99.9				
221	110000	498	108732	98.8				
226	107500	476	111192	96.7				
245	115500	471	120540	95.8				
258	125500	486	126936	98.9				
279	135000	484	137268	98.3				
319	157000	492	156948	<u>100</u>				
362	172000	475	178104	96.6				
362	182500	504	178104	97.6				
362	187500	518	178104	95.0				
366	190000	519	180072	<u>94.8</u>				

* Notice: Brinell hardness numbers (HB) were obtained by converting Rockwell hardness numbers (HRB and HRC) provided.

As can be seen from Tables 4.11A and 4.11B:

Linear regression formula provides 94.9 to 99.4% accuracy in calculating tensile strength

Statistical formula provides 94.8 to 100% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 150 to 370 HB

Appendix 4

Tensile strength of AISI Types 420 martensitic chromium stainless steel
versus Brinell hardness (3000-kgf applied load)

Table 4.12A. Linear regression formula for calculating tensile strength: $\sigma = 498 \times \text{HB} - 1193$

Brinell hardness HB*	Tensile strength, psi		Accuracy in calculating σ %	HB x σ_a	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, pp.344-346							498	-1193	0.9999
<u>193</u>	95000	94921	<u>99.9</u>	18335000	37249	9.025E+09			
195	95000	95917	<u>99.0</u>	18525000	38025	9.025E+09			
215	105000	105877	99.2	22575000	46225	1.103E+10			
<u>221</u>	110000	108865	<u>99.0</u>	24310000	48841	1.21E+10			
500	250000	247807	99.1	125000000	250000	6.25E+10			
<u>596</u>	294000	295615	99.5	175224000	355216	8.644E+10			
1,920	949,000			383969000	775556	1.901E+11			

Table 4.12B. Statistical formula for calculating tensile strength: $\sigma = 494 \times \text{HB}$

Brinell hardness HB*	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, pp.344-346		σ_a / HB			HB	σ , psi		
<u>193</u>	95000	492	95342	99.6	1,920	949,000	494	$\sigma = 494 \times \text{HB}$
195	95000	487	96330	<u>98.6</u>				
215	105000	488	106210	98.9				
<u>221</u>	110000	498	109174	99.2				
500	250000	500	247000	98.8				
<u>596</u>	294000	493	294424	<u>99.9</u>				

* Notice: Underlined Brinell hardness numbers (HB) were obtained by converting Rockwell hardness numbers (HRB and HRC) provided.

As can be seen from Tables 4.12A and 4.12B:

Linear regression formula provides 99.0 to 99.9% accuracy in calculating tensile strength

Statistical formula provides 98.6 to 99.9% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 190 to 600 HB

Appendix 4

Tensile strength of AISI Type 431 martensitic chromium-nickel stainless steel
versus Brinell hardness (3000-kgf applied load)

Table 4.13A. Linear regression formula for calculating tensile strength: $\sigma = 553 \times \text{HB} - 18263$

Brinell hardness HB*	Tensile strength, psi		Accuracy in calculating σ %	HB x σ_a	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, pp.356, 357									
260	125000	125517	<u>99.6</u>	32500000	67600	1.563E+10	553	-18263	0.9939
270	130000	131047	99.2	35100000	72900	1.69E+10			
<u>279</u>	135000	136024	99.2	37665000	77841	1.823E+10			
<u>376</u>	196000	189665	<u>96.8</u>	73696000	141376	3.842E+10			
<u>386</u>	198000	195195	98.6	76428000	148996	3.92E+10			
<u>421</u>	208000	214550	96.9	87568000	177241	4.326E+10			
1992	992000			342957000	685954	1.716E+11			

Table 4.13B. Statistical formula for calculating tensile strength: $\sigma = 498 \times \text{HB}$

Brinell hardness HB*	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, pp.356, 357		σ_a / HB	σ , psi	%				
260	125000	481	129480	96.5	1,992	992,000	498	$\sigma = 498 \times \text{HB}$
270	130000	481	134460	96.7				
<u>279</u>	135000	484	138942	97.2				
<u>376</u>	196000	521	187248	<u>95.5</u>				
<u>386</u>	198000	513	192228	97.1				
<u>421</u>	208000	494	209658	<u>99.2</u>				

* Notice: Underlined Brinell hardness numbers (HB) were obtained by converting Rockwell hardness numbers (HRC) provided.

As can be seen from Tables 4.13A and 4.13B:

Linear regression formula provides 96.8 to 99.6% accuracy in calculating tensile strength

Statistical formula provides 95.5 to 99.2% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 260 to 425 HB

Appendix 4

Tensile strength of AISI Type 440A martensitic high-chromium stainless steel
versus Brinell hardness (3000-kgf applied load)

Table 4.14A. Linear regression formula for calculating tensile strength: $\sigma = 524 \times \text{HB} - 7353$

Brinell hardness HB*	Tensile strength, psi		Accuracy in calculating σ %	HB x σ_a	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, p.359									
<u>209</u>	100000	102163	97.9	20900000	43681	1E+10	524	-7353	0.9996
<u>209</u>	105000	102163	<u>97.3</u>	21945000	43681	1.103E+10			
<u>235</u>	115000	115787	99.3	27025000	55225	1.323E+10			
510	260000	259887	<u>100</u>	132600000	260100	6.76E+10			
1163	580000			202470000	402687	1.019E+11			

Table 4.14B. Statistical formula for calculating tensile strength: $\sigma = 499 \times \text{HB}$

Brinell hardness HB*	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, p.359		σ_a / HB						
<u>209</u>	100000	478	104291	<u>95.9</u>	1,163	580,000	499	$\sigma = 499 \times \text{HB}$
<u>209</u>	105000	502	104291	<u>99.3</u>				
<u>235</u>	115000	489	117265	98.1				
510	260000	510	254490	97.9				

* Notice: Underlined Brinell hardness numbers (HB) were obtained by converting Rockwell hardness numbers (HRB) provided.

As can be seen from Tables 4.14A and 4.14B:

Linear regression formula provides 97.3 to 100% accuracy in calculating tensile strength

Statistical formula provides 95.9 to 99.3% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 205 to 510 HB

Appendix 4

Tensile strength of AISI Type 440B martensitic high-chromium stainless steel
versus Brinell hardness (3000-kgf applied load)

Table 4.15A. Linear regression formula for calculating tensile strength: $\sigma = 511 \times \text{HB} - 3677$

Brinell hardness HB*	Tensile strength, psi		Accuracy in calculating σ %	HB x σ_a	(HB) ²	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, p.364									
<u>214</u>	107000	105677	98.8	22898000	45796	1.145E+10	511	-3677	0.9999
<u>235</u>	115000	116408	<u>98.8</u>	27025000	55225	1.323E+10			
<u>242</u>	120000	119985	<u>100</u>	29040000	58564	1.44E+10			
555	280000	279928	100	155400000	308025	7.84E+10			
1246	622000			234363000	467610	1.175E+11			

Table 4.15B. Statistical formula for calculating tensile strength: $\sigma = 499 \times \text{HB}$

Brinell hardness HB*	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, p.364		σ_a / HB	σ , psi	%	HB	σ , psi	ratio σ / HB	
<u>214</u>	107000	500	106786	<u>99.8</u>	1,246	622,000	499	$\sigma = 499 \times \text{HB}$
<u>235</u>	115000	489	117265	<u>98.1</u>				
<u>242</u>	120000	496	120758	99.4				
555	280000	505	276945	98.9				

* Notice: Underlined Brinell hardness numbers (HB) were obtained by converting Rockwell hardness numbers (HRB and HRC) provided.

As can be seen from Tables 4.15A and 4.15B:

Linear regression formula provides 98.8 to 100% accuracy in calculating tensile strength

Statistical formula provides 98.1 to 99.8% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 210 to 555 HB

Appendix 4

Tensile strength of AISI Type 440C martensitic high-chromium stainless steel
versus Brinell hardness (3000-kgf applied load)

Table 4.16A. Linear regression formula for calculating tensile strength: $\sigma = 488 \times \text{HB} + 1674$

Brinell hardness HB*	Tensile strength, psi		Accuracy in calculating σ %	HB x σ_a	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, p.365									
<u>221</u>	110000	109522	99.6	24310000	48841	1.21E+10	488	1674	0.9995
<u>247</u>	125000	122210	97.8	30875000	61009	1.563E+10			
260	125000	128554	<u>97.2</u>	32500000	67600	1.563E+10			
580	285000	284714	<u>99.9</u>	165300000	336400	8.123E+10			
1308	645000			252985000	513850	1.246E+11			

Table 4.16B. Statistical formula for calculating tensile strength: $\sigma = 493 \times \text{HB}$

Brinell hardness HB*	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, p.365		σ_a / HB						
<u>221</u>	110000	498	108953	99.0	1,308	645,000	493	$\sigma = 493 \times \text{HB}$
<u>247</u>	125000	506	121771	<u>97.4</u>				
260	125000	481	128180	97.5				
580	285000	491	285940	<u>99.7</u>				

* Notice: Underlined Brinell hardness numbers (HB) were obtained by converting Rockwell hardness numbers (HRB and HRC) provided.

As can be seen from Tables 4.16A and 4.16B:

Linear regression formula provides 97.2 to 99.9% accuracy in calculating tensile strength

Statistical formula provides 97.4 to 99.7% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 220 to 580 HB

Appendix 4

Tensile strength of AISI Type 405 ferritic chromium stainless steel
versus Brinell hardness (3000-kgf applied load)

Table 4.17A. Linear regression formula for calculating tensile strength: $\sigma = 410 \times \text{HB} + 7905$

Brinell hardness HB*	Tensile strength, psi		Accuracy in calculating σ %	HB x σ_a	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, p.324									
<u>133</u>	65000	62435	96.1	8645000	17689	4.225E+09	410	7905	0.9467
150	65000	69405	<u>93.7</u>	9750000	22500	4.225E+09			
150	70000	69405	<u>99.2</u>	10500000	22500	4.9E+09			
185	85000	83755	98.5	15725000	34225	7.225E+09			
618	285000			44620000	96914	2.058E+10			

Table 4.17B. Statistical formula for calculating tensile strength: $\sigma = 461 \times \text{HB}$

Brinell hardness HB*	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, p.324		σ_a / HB	σ , psi	%	HB	σ , psi	ratio σ / HB	
<u>133</u>	65000	489	61313	94.3	618	285,000	461	$\sigma = 461 \times \text{HB}$
150	65000	433	69150	<u>94.0</u>				
150	70000	467	69150	98.8				
185	85000	459	85285	<u>99.7</u>				

* Notice: Underlined Brinell hardness number (HB) was obtained by converting Rockwell hardness number (HRB) provided.

As can be seen from Tables 4.17A and 4.17B:

Linear regression formula provides 93.7 to 99.2% accuracy in calculating tensile strength

Statistical formula provides 94.0 to 99.7% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 130 to 185 HB.

Appendix 4

Tensile strength of AISI Types 430, 434, 435, and 436 ferritic chromium stainless steels
versus Brinell hardness (3000-kgf applied load)

Table 4.18A. Linear regression formula for calculating tensile strength: $\sigma = 431 \times \text{HB} + 5810$

Brinell hardness HB*	Tensile strength, psi		Accuracy in calculating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, p.355									
<u>153</u>	70000	71753	97.6	10710000	23409	4.9E+09	431	5810	0.9708
155	75000	72615	<u>96.8</u>	11625000	24025	5.625E+09			
160	75000	74770	<u>99.7</u>	12000000	25600	5.625E+09			
<u>163</u>	75000	76063	98.6	12225000	26569	5.625E+09			
<u>182</u>	85000	84252	99.1	15470000	33124	7.225E+09			
185	85000	85545	99.4	15725000	34225	7.225E+09			
998	465000			77755000	166952	3.623E+10			

Table 4.18B. Statistical formula for calculating tensile strength: $\sigma = 466 \times \text{HB}$

Brinell hardness HB*	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, p.355		σ_a / HB						
<u>153</u>	70000	458	71298	98.2	998	465,000	466	$\sigma = 466 \times \text{HB}$
155	75000	484	72230	<u>96.3</u>				
160	75000	469	74560	99.4				
<u>163</u>	75000	460	75958	98.7				
<u>182</u>	85000	467	84812	<u>99.8</u>				
185	85000	459	86210	98.6				

* **Notice:** Underlined Brinell hardness numbers (HB) were obtained
by converting Rockwell hardness numbers (HRB) provided.

As can be seen from Tables 4.18A and 4.18B:

Linear regression formula provides 96.8 to 99.7% accuracy in calculating tensile strength

Statistical formula provides 96.3 to 99.8% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 150 to 185 HB

Appendix 4

Tensile strength of AISI Type 446 high-chromium, ferritic stainless steel
versus Brinell hardness (3000-kgf applied load)

Table 4.19A. Linear regression formula for calculating tensile strength: $\sigma = 395 \times \text{HB} + 16073$

Brinell hardness HB*	Tensile strength, psi		Accuracy in calculating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, p.370									
156	80000	77693	97.1	12480000	24336	6.4E+09	395	16073	0.9110
167	80000	82038	97.5	13360000	27889	6.4E+09			
182	85000	87963	96.6	15470000	33124	7.225E+09			
193	95000	92308	97.2	18335000	37249	9.025E+09			
698	340000			59645000	122598	2.905E+10			

Table 4.19B. Statistical formula for calculating tensile strength: $\sigma = 487 \times \text{HB}$

Brinell hardness HB*	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, p.370		σ_a / HB	σ , psi	%	HB	σ , psi	ratio σ / HB	
156	80000	513	75972	95.0	698	340,000	487	$\sigma = 487 \times \text{HB}$
167	80000	479	81329	98.4				
182	85000	467	88634	95.9				
193	95000	492	93991	98.9				

* Notice: Brinell hardness numbers (HB) were obtained by converting Rockwell hardness numbers (HRB) provided.

As can be seen from Tables 4.19A and 4.19B:

Linear regression formula provides 96.6 to 97.5% accuracy in calculating tensile strength

Statistical formula provides 95.0 to 98.9% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 155 to 195 HB

Appendix 4

Tensile strength of UNS S13800 (PH 13-8 Mo) martensitic,
precipitation-hardening stainless steel versus Brinell hardness (3000-kgf applied load)

Table 4.20A. Linear regression formula for calculating tensile strength: $\sigma = 578 \times \text{HB} - 32192$

Brinell hardness HB*	Tensile strength, psi		Accuracy in calculating σ %	HB x σ_a	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, p.403									
272	130000	125024	96.2	35360000	73984	1.69E+10	578	-32192	0.9925
310	145000	146988	98.6	44950000	96100	2.103E+10			
336	160000	162016	98.8	53760000	112896	2.56E+10			
401	190000	199586	<u>95.2</u>	76190000	160801	3.61E+10			
421	215000	211146	98.2	90515000	177241	4.623E+10			
443	225000	223862	<u>99.5</u>	99675000	196249	5.063E+10			
456	235000	231376	98.5	107160000	207936	5.523E+10			
2639	1300000			507610000	1025207	2.517E+11			

Table 4.20B. Statistical formula for calculating tensile strength: $\sigma = 493 \times \text{HB}$

Brinell hardness HB*	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, p.403		σ_a / HB	σ , psi	%	HB	σ , psi	ratio σ / HB	
272	130000	478	134096	96.9	2,639	1,300,000	493	$\sigma = 493 \times \text{HB}$
310	145000	468	152830	<u>94.9</u>				
336	160000	476	165648	96.6				
401	190000	474	197693	96.1				
421	215000	511	207553	96.5				
443	225000	508	218399	<u>97.1</u>				
456	235000	515	224808	95.7				

* Notice: Brinell hardness numbers (HB) were obtained
by converting Rockwell hardness numbers (HRC) provided.

As can be seen from Tables 4.20A and 4.20B:

Linear regression formula provides 95.2 to 99.5% accuracy in calculating tensile strength

Statistical formula provides 94.9 to 97.1% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 270 to 460 HB

Appendix 4

Tensile strength of UNS S15500 (15-5 PH) martensitic,
precipitation-hardening stainless steel versus Brinell hardness (3000-kgf applied load)

Table 4.21A. Linear regression formula for calculating tensile strength: $\sigma = 505 \times \text{HB} - 12601$

Brinell hardness HB	Tensile strength, psi		Accuracy in calculating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, p.406									
277	125000	127284	98.2	34625000	76729	1.563E+10	505	-12601	0.9878
311	145000	144454	99.6	45095000	96721	2.103E+10			
332	150000	155059	<u>96.7</u>	49800000	110224	2.25E+10			
341	165000	159604	<u>96.7</u>	56265000	116281	2.723E+10			
352	170000	165159	97.2	59840000	123904	2.89E+10			
409	190000	193944	98.0	77710000	167281	3.61E+10			
420	200000	199499	<u>99.7</u>	84000000	176400	4E+10			
2442	1145000			407335000	867540	1.914E+11			

Table 4.21B. Statistical formula for calculating tensile strength: $\sigma = 469 \times \text{HB}$

Brinell hardness HB	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, p.406		σ_a / HB						
277	125000	451	129913	<u>96.2</u>	2,442	1,145,000	469	$\sigma = 469 \times \text{HB}$
311	145000	466	145859	<u>99.4</u>				
332	150000	452	155708	96.3				
341	165000	484	159929	96.9				
352	170000	483	165088	97.1				
409	190000	465	191821	99.1				
420	200000	476	196980	98.5				

As can be seen from Tables 4.21A and 4.21B:

Linear regression formula provides 96.7 to 99.7% accuracy in calculating tensile strength

Statistical formula provides 96.2 to 99.4% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 275 to 420 HB

Appendix 4

Tensile strength of AISI Type 630 (UNS S17400)
precipitation-hardening, martensitic stainless steel versus Brinell hardness (3000-kgf applied load)

Table 4.22A. Linear regression formula for calculating tensile strength: $\sigma = 523 \times \text{HB} - 18525$

Brinell hardness HB	Tensile strength, psi		Accuracy in calculating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, p.375									
277	123000	126346	97.4	34071000	76729	1.513E+10	523	-18525	0.9929
311	144000	144128	99.9	44784000	96721	2.074E+10			
341	164000	159818	97.5	55924000	116281	2.69E+10			
352	168000	165571	98.6	59136000	123904	2.822E+10			
420	198000	201135	98.4	83160000	176400	3.92E+10			
1701	797000			277075000	590035	1.302E+11			

Table 4.22B. Statistical formula for calculating tensile strength: $\sigma = 469 \times \text{HB}$

Brinell hardness HB	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, p.375		σ_a / HB						
277	123000	444	129913	94.7	1,701	797,000	469	$\sigma = 469 \times \text{HB}$
311	144000	463	145859	98.7				
341	164000	481	159929	97.5				
352	168000	477	165088	98.3				
420	198000	471	196980	99.5				

As can be seen from Tables 4.22A and 4.22B:

Linear regression formula provides 97.4 to 99.9% accuracy in calculating tensile strength

Statistical formula provides 94.7 to 99.5% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 275 to 420 HB

Appendix 4

Tensile strength of AISI Type 631, (UNS S17700)
precipitation-hardening stainless steel versus Brinell hardness (3000-kgf applied load)

Table 4.23A. Linear regression formula for calculating tensile strength: $\sigma = 754 \times \text{HB} - 87691$

Brinell hardness HB*	Tensile strength, psi		Accuracy in calculating σ %	HB x σ_a	(HB) ²	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 7, p.864									
353	180000	178471	99.2	63540000	124609	3.24E+10	754	-87691	0.9915
381	200000	199583	99.8	76200000	145161	4E+10			
401	210000	214663	97.8	84210000	160801	4.41E+10			
431	240000	237283	98.9	103440000	185761	5.76E+10			
1566	830000			327390000	616332	1.741E+11			

Table 4.23B. Statistical formula for calculating tensile strength: $\sigma = 530 \times \text{HB}$

Brinell hardness HB*	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 7, p.864		σ_a / HB						
353	180000	510	187090	96.2	1,566	830,000	530	$\sigma = 530 \times \text{HB}$
381	200000	525	201930	99.0				
401	210000	524	212530	98.8				
431	240000	557	228430	95.2				

* Notice: Brinell hardness numbers (HB) were obtained
by converting Rockwell hardness numbers (HRC) provided.

As can be seen from Tables 4.23A and 4.23B:

Linear regression formula provides 97.8 to 99.8% accuracy in calculating tensile strength

Statistical formula provides 95.2 to 99.0% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 350 to 435 HB

Appendix 4

Tensile strength of UNS S45000 (Custom 450) martensitic,
precipitation-hardening stainless steel versus Brinell hardness (3000-kgf applied load)

Table 4.24A. Linear regression formula for calculating tensile strength: $\sigma = 526 \times \text{HB} - 15863$

Brinell hardness HB*	Tensile strength, psi		Accuracy in calculating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
(Ref 7, 8)**									
258	125000	119845	95.9	32250000	66564	1.563E+10	526	-15863	0.9856
286	130000	134573	96.6	37180000	81796	1.69E+10			
319	145000	151931	95.4	46255000	101761	2.103E+10			
319	150000	151931	98.7	47850000	101761	2.25E+10			
336	160000	160873	99.5	53760000	112896	2.56E+10			
344	170000	165081	97.1	58480000	118336	2.89E+10			
362	180000	174549	97.0	65160000	131044	3.24E+10			
371	180000	179283	99.6	66780000	137641	3.24E+10			
386	187000	187173	99.9	72182000	148996	3.497E+10			
396	195000	192433	98.7	77220000	156816	3.803E+10			
411	196000	200323	97.8	80556000	168921	3.842E+10			
3788	1818000			637673000	1326532	3.068E+11			

Table 4.24B. Statistical formula for calculating tensile strength: $\sigma = 480 \times \text{HB}$

Brinell hardness HB*	Tensile strength σ _a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula	Accuracy in calculating σ	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ, psi		
(Ref 7, 8)**		σ _a / HB	σ, psi	%	HB	σ, psi		
258	125000	484	123840	99.1	3,788	1,818,000	480	σ = 480 x HB
286	130000	455	137280	94.7				
319	145000	455	153120	94.7				
319	150000	470	153120	98.0				
336	160000	476	161280	99.2				
344	170000	494	165120	97.1				
362	180000	497	173760	96.5				
371	180000	485	178080	98.9				
386	187000	484	185280	99.1				
396	195000	492	190080	97.5				
411	196000	477	197280	99.4				

* **Notice:** Brinell hardness numbers (HB) were obtained
by converting Rockwell hardness numbers (HRC) provided.

** Ref 7, pp.864, 865; Ref 8, p.425.

As can be seen from Tables 4.24A and 4.24B:

Linear regression formula provides 95.4 to 99.9% accuracy in calculating tensile strength

Statistical formula provides 94.7 to 99.4% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 255 to 415 HB

Appendix 4

Tensile strength of UNS S45500 (Custom 455) martensitic,
precipitation-hardening stainless steel versus Brinell hardness (3000-kgf applied load)

Table 4.25A. Linear regression formula for calculating tensile strength: $\sigma = 565 \times \text{HB} - 24104$

Brinell hardness HB*	Tensile strength, psi		Accuracy in calculating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref. 8, p.427							565	-24104	0.9903
294	140000	142006	98.6	41160000	86436	1.96E+10			
294	145000	142006	97.9	42630000	86436	2.103E+10			
371	190000	185511	97.6	70490000	137641	3.61E+10			
421	205000	213761	<u>95.9</u>	86305000	177241	4.203E+10			
421	210000	213761	98.2	88410000	177241	4.41E+10			
456	230000	233536	98.5	104880000	207936	5.29E+10			
456	235000	233536	<u>99.4</u>	107160000	207936	5.523E+10			
469	250000	240881	96.4	117250000	219961	6.25E+10			
3182	1605000			658285000	1300828	3.335E+11			

Table 4.25B. Statistical formula for calculating tensile strength: $\sigma = 504 \times \text{HB}$

Brinell hardness HB*	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref. 8, p.427		σ_a / HB						
294	140000	476	148176	<u>94.5</u>	3,182	1,605,000	504	$\sigma = 504 \times \text{HB}$
294	145000	493	148176	97.9				
371	190000	512	186984	98.4				
421	205000	487	212184	96.6				
421	210000	499	212184	99.0				
456	230000	504	229824	<u>99.9</u>				
456	235000	515	229824	97.8				
469	250000	533	236376	94.6				

* Notice: Brinell hardness numbers (HB) were obtained
by converting Rockwell hardness numbers (HRC) provided.

As can be seen from Tables 4.25A and 4.25B:

Linear regression formula provides 95.9 to 99.4% accuracy in calculating tensile strength

Statistical formula provides 94.5 to 99.9% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 290 to 470 HB

APPENDIX 5. TOOL STEELS

TENSILE STRENGTH versus BRINELL HARDNESS

Tables 5.1A and 5.1B. AISI type W1 (UNS T72301) water-hardening steel
Tables 5.2A and 5.2B. AISI type S1 (UNS T41901) shock-resisting steel
Tables 5.3A and 5.3B. AISI type S2 (UNS T41902) shock-resisting steel
Tables 5.4A and 5.4B. AISI type S5 (UNS T41905) shock-resisting steel
Tables 5.5A and 5.5B. AISI type S7 (UNS T41907) shock-resisting steel
Tables 5.6A and 5.6B. AISI type O1 (UNS T31501) oil-hardening cold-work steel
Tables 5.7A and 5.7B. AISI type O2 (UNS T31502) oil-hardening cold-work steel
Tables 5.8A and 5.8B. AISI type O7 (UNS T31507) oil-hardening cold-work steel
Tables 5.9A and 5.9B. AISI type A2 (UNS T30102) air-hardening cold-work steel
Tables 5.10A and 5.10B. AISI type A6 (UNS T30106) air-hardening cold-work steel
Tables 5.11A and 5.11B. AISI type P6 (UNS T51606) mold steel
Tables 5.12A and 5.12B. AISI type P20 (UNS T51620) mold steel
Tables 5.13A and 5.13B. AISI type L2 (UNS T61202) low-alloy special-purpose steel
Tables 5.14A and 5.14B. AISI type L6 (UNS T61206) low-alloy special-purpose steel
Tables 5.15A and 5.15B. AISI types H11 (UNS T20811) and H13 (T20813) hot-work steel
Tables 5.16A and 5.16B. AISI type H12 (UNS T20812) hot-work steel
Tables 5.17A and 5.17B. AISI type H21 (UNS T20821) hot-work steel

Appendix 5

Tensile strength of AISI Type W1 (UNS T72301) water-hardening steel
versus Brinell hardness (3000-kgf applied load)

Table 5.1A. Linear regression formula for calculating tensile strength: $\sigma = 379 \times \text{HB} + 47330$

Brinell hardness HB*	Tensile strength, psi		Accuracy in calculating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a^{**}	calculated by the above formula, σ					slope	intercept	
Ref 8, p.436, Graph									
226	120600	132984	<u>90.7</u>	27255600	51076	1.454E+10	379	47330	0.9615
247	136800	140943	97.1	33789600	61009	1.871E+10			
272	154000	150418	97.7	41888000	73984	2.372E+10			
302	170200	161788	95.1	51400400	91204	2.897E+10			
336	184000	174674	94.9	61824000	112896	3.386E+10			
371	195600	187939	96.1	72567600	137641	3.826E+10			
411	202500	203099	<u>99.7</u>	83227500	168921	4.101E+10			
456	208300	220154	94.6	94984800	207936	4.339E+10			
2,621	1,372,000			466937500	904667	2.425E+11			

Table 5.1B. Statistical formula for calculating tensile strength: $\sigma = 523 \times \text{HB}$

Brinell hardness HB*	Tensile strength σ_a^{**} , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, p.436, Graph		σ_a / HB						
226	120600	534	118198	98.0	2,621	1,372,000	523	$\sigma = 523 \times \text{HB}$
247	136800	554	129181	94.4				
272	154000	566	142256	92.4				
302	170200	564	157946	92.8				
336	184000	548	175728	95.5				
371	195600	527	194033	<u>99.2</u>				
411	202500	493	214953	94.2				
456	208300	457	238488	<u>87.3</u>				

* Brinell hardness numbers (HB) were obtained
by converting Rockwell hardness HRC shown on the graph.

** Tensile strength values were determined from the graph.

As can be seen from Tables 5.1A and 5.1B:

Linear regression formula provides 90.7 to 99.7% accuracy in calculating tensile strength

Statistical formula provides 87.3 to 99.2% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 225 to 460 HB

Appendix 5

Tensile strength of AISI Type S1 (UNS T41901) shock-resisting steel
versus Brinell hardness (3000-kgf applied load)

Table 5.2A. Linear regression formula for calculating tensile strength: $\sigma = 543 \times \text{HB} - 11459$

Brinell hardness HB*	Tensile strength, psi		Accuracy in calcu- lating σ %	HB x σ_a	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 7, p.767							543	-11459	0.9890
214	100000	104743	95.5	21400000	45796	1E+10			
391	195000	200854	97.1	76245000	152881	3.803E+10			
450	244000	232891	95.4	109800000	202500	5.954E+10			
488	260000	253525	<u>97.5</u>	126880000	238144	6.76E+10			
544	294000	283933	96.6	159936000	295936	8.644E+10			
605	300000	317056	<u>94.6</u>	181500000	366025	9E+10			
2,692	1,393,000			675761000	1301282	3.516E+11			

Table 5.2B. Statistical formula for calculating tensile strength: $\sigma = 517 \times \text{HB}$

Brinell hardness HB*	Tensile strength σ_a , psi	Strength-to- hardness ratio	Tensile strength calculated by the above formula	Accuracy in calcu- lating σ	Cumulative values:		Average strength-to- hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 7, p.767		σ_a / HB	σ , psi	%	HB	σ , psi	ratio σ / HB	
214	100000	467	110638	<u>90.4</u>	2,692	1,393,000	517	$\sigma = 517 \times \text{HB}$
391	195000	499	202147	96.5				
450	244000	542	232650	95.3				
488	260000	533	252296	<u>97.0</u>				
544	294000	540	281248	95.7				
605	300000	496	312785	95.9				

* Notice: Brinell hardness numbers (HB) were obtained
by converting Rockwell hardness numbers (HRB and HRC) provided.

As can be seen from Tables 5.2A and 5.2B:

Linear regression formula provides 94.6 to 97.5% accuracy in calculating tensile strength

Statistical formula provides 90.4 to 97.0% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 210 to 605 HB

Appendix 5

Tensile strength of AISI Type S2 (UNS T41902) shock-resisting steel
versus Brinell hardness (3000-kgf applied load)

Table 5.3A. Linear regression formula for calculating tensile strength: $\sigma = 631 \times \text{HB} - 50131$

Brinell hardness HB*	Tensile strength, psi		Accuracy in calculating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a^{**}	calculated by the above formula, σ					slope	intercept	
Ref 8, p.439, Graph									
226	103200	92475	<u>89.6</u>	23323200	51076	1.065E+10	631	-50131	0.9929
253	114200	109512	95.9	28892600	64009	1.304E+10			
286	128300	130335	98.4	36693800	81796	1.646E+10			
327	147200	156206	94.2	48134400	106929	2.167E+10			
371	172300	183970	93.7	63923300	137641	2.969E+10			
421	208300	215520	96.6	87694300	177241	4.339E+10			
480	263300	252749	96.0	126384000	230400	6.933E+10			
560	307200	303229	<u>98.7</u>	172032000	313600	9.437E+10			
2,924	1,444,000			587077600	1162692	2.986E+11			

Table 5.3B. Statistical formula for calculating tensile strength: $\sigma = 494 \times \text{HB}$

Brinell hardness HB*	Tensile strength σ_a^{**} , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, p.439, Graph		σ_a / HB						
226	103200	457	111644	92.4	2,924	1,444,000	494	$\sigma = 494 \times \text{HB}$
253	114200	451	124982	91.4				
286	128300	449	141284	90.8				
327	147200	450	161538	91.1				
371	172300	464	183274	94.0				
421	208300	495	207974	<u>99.8</u>				
480	263300	549	237120	<u>90.1</u>				
560	307200	549	276640	90.1				

* Brinell hardness numbers (HB) were obtained
by converting Rockwell hardness HRC shown on the graph.

** Tensile strength values were determined from the graph.

As can be seen from Tables 5.3A and 5.3B:

Linear regression formula provides 89.6 to 98.7% accuracy in calculating tensile strength

Statistical formula provides 90.1 to 99.8% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 225 to 560 HB

Appendix 5

Tensile strength of AISI Type S5 (UNS T41905) shock-resisting steel
versus Brinell hardness (3000-kgf applied load)

Table 5.4A. Linear regression formula for calculating tensile strength: $\sigma = 561 \times \text{HB} - 19646$

Brinell hardness HB*	Tensile strength, psi		Accuracy in calculating σ %	HB x σ_a	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 7, p.767									
214	105000	100408	95.6	22470000	45796	1.103E+10	561	-19646	0.9951
456	220000	236170	<u>93.2</u>	100320000	207936	4.84E+10			
512	275000	267586	97.3	140800000	262144	7.563E+10			
614	325000	324808	<u>99.9</u>	199550000	376996	1.056E+11			
634	340000	336028	98.8	215560000	401956	1.156E+11			
2,430	1,265,000			678700000	1294828	3.563E+11			

Table 5.4B. Statistical formula for calculating tensile strength: $\sigma = 521 \times \text{HB}$

Brinell hardness HB*	Tensile strength σ _a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula	Accuracy in calculating σ	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ, psi		
Ref 7, p.767		σ _a / HB	σ, psi	%	HB	σ, psi		
214	105000	491	111494	94.2	2,430	1,265,000	521	σ = 521 x HB
456	220000	482	237576	<u>92.6</u>				
512	275000	537	266752	97.0				
614	325000	529	319894	<u>98.4</u>				
634	340000	536	330314	97.2				

* Notice: Brinell hardness numbers (HB) were obtained
by converting Rockwell hardness numbers (HRB and HRC) provided.

As can be seen from Tables 5.4A and 5.4B:

Linear regression formula provides 93.2 to 99.9% accuracy in calculating tensile strength

Statistical formula provides 92.6 to 98.4% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 210 to 635 HB

Appendix 5

Tensile strength of AISI Type S7 (UNS T41907) shock-resisting steel
versus Brinell hardness (3000-kgf applied load)

Table 5.5A. Linear regression formula for calculating tensile strength: $\sigma = 553 \times \text{HB} - 19876$

Brinell hardness HB*	Tensile strength, psi		Accuracy in calculating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 7, p.767							553	-19876	0.9978
209	93000	95701	97.2	19437000	43681	8.649E+09			
362	180000	180310	99.8	65160000	131044	3.24E+10			
496	264000	254412	96.4	130944000	246016	6.97E+10			
528	275000	272108	98.9	145200000	278784	7.563E+10			
560	285000	289804	98.3	159600000	313600	8.123E+10			
614	315000	319666	98.5	193410000	376996	9.923E+10			
2,769	1,412,000			713751000	1390121	3.668E+11			

Table 5.5B. Statistical formula for calculating tensile strength: $\sigma = 510 \times \text{HB}$

Brinell hardness HB*	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 7, p.767		σ_a / HB						
209	93000	445	106590	87.3	2,769	1,412,000	510	$\sigma = 510 \times \text{HB}$
362	180000	497	184620	97.5				
496	264000	532	252960	95.8				
528	275000	521	269280	97.9				
560	285000	509	285600	99.8				
614	315000	513	313140	99.4				

* Notice: Brinell hardness numbers (HB) were obtained
by converting Rockwell hardness numbers (HRB and HRC) provided.

As can be seen from Tables 5.5A and 5.5B:

Linear regression formula provides 96.4 to 99.8% accuracy in calculating tensile strength

Statistical formula provides 87.3 to 99.8% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 205 to 615 HB

Appendix 5

Tensile strength of AISI Type O1 (UNS T31501) oil-hardening cold-work steel
versus Brinell hardness (3000-kgf applied load)

Table 5.6A. Linear regression formula for calculating tensile strength: $\sigma = 546 \times \text{HB} - 26657$

Brinell hardness HB*	Tensile strength, psi		Accuracy in calculating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 14, p.187							546	-26657	0.9806
237	112000	102745	91.7	26544000	56169	1.254E+10			
294	133000	133867	99.4	39102000	86436	1.769E+10			
362	159000	170995	93.0	57558000	131044	2.528E+10			
411	187000	197749	94.6	76857000	168921	3.497E+10			
443	217000	215221	99.2	96131000	196249	4.709E+10			
480	248000	235423	94.9	119040000	230400	6.15E+10			
2,227	1,056,000			415232000	869219	1.991E+11			

Table 5.6B. Statistical formula for calculating tensile strength: $\sigma = 474 \times \text{HB}$

Brinell hardness HB*	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 14, p.187		σ_a / HB						
237	112000	473	112338	99.7	2,227	1,056,000	474	$\sigma = 474 \times \text{HB}$
294	133000	452	139356	95.4				
362	159000	439	171588	92.7				
411	187000	455	194814	96.0				
443	217000	490	209982	96.8				
480	248000	517	227520	91.7				

* Notice: Brinell hardness numbers (HB) were obtained by converting Rockwell hardness numbers (HRC) provided.

As can be seen from Tables 5.6A and 5.6B:

Linear regression formula provides 91.7 to 99.4% accuracy in calculating tensile strength

Statistical formula provides 91.7 to 99.7% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 235 to 480 HB

Appendix 5

Tensile strength of AISI Type O2 (UNS T31502) oil-hardening cold-work steel
versus Brinell hardness (3000-kgf applied load)

Table 5.7A. Linear regression formula for calculating tensile strength: $\sigma = 545 \times \text{HB} - 15192$

Brinell hardness HB*	Tensile strength, psi		Accuracy in calculating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a^{**}	calculated by the above formula, σ					slope	intercept	
Ref 8, p.444, Graph									
226	105500	107978	<u>97.7</u>	23843000	51076	1.113E+10	545	-15192	0.9987
253	120500	122693	98.2	30486500	64009	1.452E+10			
286	142100	140678	99.0	40640600	81796	2.019E+10			
327	163700	163023	<u>99.6</u>	53529900	106929	2.68E+10			
371	188600	187003	99.2	69970600	137641	3.557E+10			
421	218500	214253	98.1	91988500	177241	4.774E+10			
480	248400	246408	99.2	119232000	230400	6.17E+10			
539	273300	278563	98.1	147308700	290521	7.469E+10			
2,903	1,460,600			576999800	1139613	2.923E+11			

Table 5.7B. Statistical formula for calculating tensile strength: $\sigma = 503 \times \text{HB}$

Brinell hardness HB*	Tensile strength σ_a^{**} , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, p.444, Graph		σ_a / HB	σ , psi					
226	105500	467	113678	<u>92.8</u>	2,903	1,460,600	503	$\sigma = 503 \times \text{HB}$
253	120500	476	127259	94.7				
286	142100	497	143858	98.8				
327	163700	501	164481	<u>99.5</u>				
371	188600	508	186613	98.9				
421	218500	519	211763	96.9				
480	248400	518	241440	97.2				
539	273300	507	271117	99.2				

- * Brinell hardness numbers (HB) were obtained
by converting Rockwell hardness HRC shown on the graph.
- ** Tensile strength values were determined from the graph.

As can be seen from Tables 5.7A and 5.7B:

Linear regression formula provides 97.7 to 99.6% accuracy in calculating tensile strength

Statistical formula provides 92.8 to 99.5% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 225 to 540 HB

Appendix 5

Tensile strength of AISI Type O7 (UNS T31507) oil-hardening cold-work steel
versus Brinell hardness (3000-kgf applied load)

Table 5.8A. Linear regression formula for calculating tensile strength: $\sigma = 593 \times \text{HB} - 51470$

Brinell hardness HB*	Tensile strength, psi		Accuracy in calculating σ %	HB x σ_a	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 14, p.187							593	-51470	0.9959
293	128000	122279	95.5	37504000	85849	1.638E+10			
373	161000	169719	94.9	60053000	139129	2.592E+10			
441	209000	210043	99.5	92169000	194481	4.368E+10			
486	237000	236728	99.9	115182000	236196	5.617E+10			
514	258000	253332	98.2	132612000	264196	6.656E+10			
547	272000	272901	99.7	148784000	299209	7.398E+10			
2,654	1,265,000			586304000	1219060	2.827E+11			

Table 5.8B. Statistical formula for calculating tensile strength: $\sigma = 477 \times \text{HB}$

Brinell hardness HB*	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 14, p.187		σ_a / HB	σ , psi	%	HB	σ , psi	ratio σ / HB	strength
293	128000	437	139761	91.6	2,654	1,265,000	477	$\sigma = 477 \times \text{HB}$
373	161000	432	177921	90.5				
441	209000	474	210357	99.4				
486	237000	488	231822	97.8				
514	258000	502	245178	95.0				
547	272000	497	260919	95.9				

* Notice: Brinell hardness numbers (HB) were obtained
by converting Rockwell hardness numbers (HRC) provided.

As can be seen from Tables 5.8A and 5.8B:

Linear regression formula provides 94.9 to 99.9% accuracy in calculating tensile strength

Statistical formula provides 90.5 to 99.4% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 290 to 550 HB

Appendix 5

Tensile strength of AISI Type A2 (UNS T30102) air-hardening cold-work steel
versus Brinell hardness (3000-kgf applied load)

Table 5.9A. Linear regression formula for calculating tensile strength: $\sigma = 552 \times \text{HB} - 25062$

Brinell hardness HB*	Tensile strength, psi		Accuracy in calculating σ %	HB x σ_a	(HB) ²	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a^{**}	calculated by the above formula, σ					slope	intercept	
Ref 8, p.447, Graph							552	-25062	0.9986
226	104700	99690	<u>95.2</u>	23662200	51076	1.096E+10			
253	112500	114594	98.2	28462500	64009	1.266E+10			
286	128100	132810	96.5	36636600	81796	1.641E+10			
327	153100	155442	98.5	50063700	106929	2.344E+10			
371	181300	179730	99.1	67262300	137641	3.287E+10			
421	210900	207330	98.3	88788900	177241	4.448E+10			
480	240600	239898	<u>99.7</u>	115488000	230400	5.789E+10			
496	250000	248730	99.5	124000000	246016	6.25E+10			
520	259000	261978	98.9	134680000	270400	6.708E+10			
3,380	1,640,200			669044200	1365508	3.283E+11			

Table 5.9B. Statistical formula for calculating tensile strength: $\sigma = 485 \times \text{HB}$

Brinell hardness HB*	Tensile strength σ_a^{**} , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, p.447, Graph		σ_a / HB			HB	σ , psi		
226	104700	463	109610	95.5	3,380	1,640,200	485	$\sigma = 485 \times \text{HB}$
253	112500	445	122705	<u>91.7</u>				
286	128100	448	138710	92.4				
327	153100	468	158595	96.5				
371	181300	489	179935	<u>99.2</u>				
421	210900	501	204185	96.8				
480	240600	501	232800	96.8				
496	250000	504	240560	96.2				
520	259000	498	252200	97.4				

* Brinell hardness numbers (HB) were obtained
by converting Rockwell hardness HRC shown on the graph.

** Tensile strength values were determined from the graph.

As can be seen from Tables 5.9A and 5.9B:

Linear regression formula provides 95.2 to 99.7% accuracy in calculating tensile strength

Statistical formula provides 91.7 to 99.2% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 225 to 520 HB

Appendix 5

Tensile strength of AISI Type A6 (UNS T30106) air-hardening cold-work steel
versus Brinell hardness (3000-kgf applied load)

Table 5.10A. Linear regression formula for calculating tensile strength: $\sigma = 572 \times \text{HB} - 3689$

Brinell hardness HB*	Tensile strength, psi		Accuracy in calculating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a^{**}	calculated by the above formula, σ					slope	intercept	
Ref 8, p.447, Graph									
480	261200	270871	<u>96.4</u>	125376000	230400	6.823E+10	572	-3689	0.9720
496	277100	280023	99.0	137441600	246016	7.678E+10			
512	291900	289175	99.1	149452800	262144	8.521E+10			
528	304200	298327	98.1	160617600	278784	9.254E+10			
544	314400	307479	97.8	171033600	295936	9.885E+10			
560	322400	316631	98.2	180544000	313600	1.039E+11			
577	329200	326355	99.1	189948400	332929	1.084E+11			
596	334500	337223	<u>99.2</u>	199362000	355216	1.119E+11			
614	338700	347519	97.5	207961800	376996	1.147E+11			
4,907	2,773,600			1.522E+09	2692021	8.605E+11			

Table 5.10B. Statistical formula for calculating tensile strength: $\sigma = 565 \times \text{HB}$

Brinell hardness HB*	Tensile strength σ_a^{**} , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, p.447, Graph		σ_a / HB						
480	261200	544	271200	<u>96.3</u>	4,907	2,773,600	565	$\sigma = 565 \times \text{HB}$
496	277100	559	280240	98.9				
512	291900	570	289280	99.1				
528	304200	576	298320	98.1				
544	314400	578	307360	97.8				
560	322400	576	316400	98.1				
577	329200	571	326005	99.0				
596	334500	561	336740	<u>99.3</u>				
614	338700	552	346910	97.6				

* Brinell hardness numbers (HB) were obtained
by converting Rockwell hardness HRC shown on the graph.

** Tensile strength values were determined from the graph.

As can be seen from Tables 5.10A and 5.10B:

Linear regression formula provides 96.4 to 99.2% accuracy in calculating tensile strength

Statistical formula provides 96.3 to 99.3% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 480 to 615 HB

Appendix 5

Tensile strength of AISI Type P6 (UNS T51606) mold steel
versus Brinell hardness (3000-kgf applied load)

Table 5.11A. Linear regression formula for calculating tensile strength: $\sigma = 510 \times \text{HB} - 6106$

Brinell hardness HB*	Tensile strength, psi		Accuracy in calculating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a^{**}	calculated by the above formula, σ					slope	intercept	
Ref 8, p.456, Graph							510	-6106	0.9980
226	111800	109154	97.6	25266800	51076	1.25E+10			
237	115800	114764	99.1	27444600	56169	1.341E+10			
247	119700	119864	99.9	29565900	61009	1.433E+10			
258	125000	125474	99.6	32250000	66564	1.563E+10			
272	131600	132614	99.2	35795200	73984	1.732E+10			
286	138200	139754	98.9	39525200	81796	1.91E+10			
302	146000	147914	98.7	44092000	91204	2.132E+10			
319	155300	156584	99.2	49540700	101761	2.412E+10			
336	164500	165254	99.5	55272000	112896	2.706E+10			
353	175000	173924	99.4	61775000	124609	3.063E+10			
371	185500	183104	98.7	68820500	137641	3.441E+10			
3,207	1,568,400			469347900	958709	2.298E+11			

Table 5.11B. Statistical formula for calculating tensile strength: $\sigma = 489 \times \text{HB}$

Brinell hardness HB*	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, p.456, Graph		σ_a / HB	σ , psi	%	HB	σ , psi	ratio σ / HB	strength
226	111800	495	110514	98.8	3,207	1,568,400	489	$\sigma = 489 \times \text{HB}$
237	115800	489	115893	99.9				
247	119700	485	120783	99.1				
258	125000	484	126162	99.1				
272	131600	484	133008	98.9				
286	138200	483	139854	98.8				
302	146000	483	147678	98.9				
319	155300	487	155991	99.6				
336	164500	490	164304	99.9				
353	175000	496	172617	98.6				
371	185500	500	181419	97.8				

- * Brinell hardness numbers (HB) were obtained
by converting Rockwell hardness HRC shown on the graph.
- ** Tensile strength values were determined from the graph.

As can be seen from Tables 5.11A and 5.11B:

Linear regression formula provides 97.6 to 99.9% accuracy in calculating tensile strength

Statistical formula provides 97.8 to 99.9% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 225 to 375 HB

Appendix 5

Tensile strength of AISI Type P20 (UNS T51620) mold steel
versus Brinell hardness (3000-kgf applied load)

Table 5.12A. Linear regression formula for calculating tensile strength: $\sigma = 543 \times \text{HB} - 11173$

Brinell hardness HB*	Tensile strength, psi		Accuracy in calculating σ %	HB x σ_a	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 8, p.454							543	-11173	0.9980
258	130000	128921	99.2	33540000	66564	1.69E+10			
286	144000	144125	99.9	41184000	81796	2.074E+10			
327	168000	166388	99.0	54936000	106929	2.822E+10			
353	180000	180506	99.7	63540000	124609	3.24E+10			
381	192000	195710	98.1	73152000	145161	3.686E+10			
411	207000	212000	97.6	85077000	168921	4.285E+10			
431	224000	222860	99.5	96544000	185761	5.018E+10			
456	242000	236435	97.7	110352000	207936	5.856E+10			
480	254000	249467	98.2	121920000	230400	6.452E+10			
512	262000	266843	98.2	134144000	262144	6.864E+10			
528	276000	275531	99.8	145728000	278784	7.618E+10			
544	284000	284219	99.9	154496000	295936	8.066E+10			
4,967	2,563,000			1.115E+09	2154941	5.767E+11			

Table 5.12B. Statistical formula for calculating tensile strength: $\sigma = 516 \times \text{HB}$

Brinell hardness HB*	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, p.454		σ_a / HB						
258	130000	504	133128	97.7	4,967	2,563,000	516	$\sigma = 516 \times \text{HB}$
286	144000	503	147576	97.6				
327	168000	514	168732	99.6				
353	180000	510	182148	98.8				
381	192000	504	196596	97.7				
411	207000	504	212076	97.6				
431	224000	520	222396	99.3				
456	242000	531	235296	97.2				
480	254000	529	247680	97.5				
512	262000	512	264192	99.2				
528	276000	523	272448	98.7				
544	284000	522	280704	98.8				

* Notice: Brinell hardness numbers (HB) were obtained
by converting Rockwell hardness numbers (HRC) provided.

As can be seen from Tables 5.12A and 5.12B:

Linear regression formula provides 97.6 to 99.9% accuracy in calculating tensile strength

Statistical formula provides 97.2 to 99.6% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 255 to 545 HB

Appendix 5

Tensile strength of AISI Type L2 (UNS T61202) low-alloy special-purpose steel
versus Brinell hardness (3000-kgf applied load)

Table 5.13A. Linear regression formula for calculating tensile strength: $\sigma = 560 \times \text{HB} - 22467$

Brinell hardness HB*	Tensile strength, psi		Accuracy in calculating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 7, p.767									
214	103000	97373	<u>94.5</u>	22042000	45796	1.061E+10	560	-22467	0.9971
286	135000	137693	98.0	38610000	81796	1.823E+10			
381	185000	190893	96.9	70485000	145161	3.423E+10			
443	225000	225613	<u>99.7</u>	99675000	196249	5.063E+10			
512	260000	264253	98.4	133120000	262144	6.76E+10			
544	290000	282173	97.3	157760000	295936	8.41E+10			
2,380	1,198,000			521692000	1027082	2.654E+11			

Table 5.13B. Statistical formula for calculating tensile strength: $\sigma = 503 \times \text{HB}$

Brinell hardness HB*	Tensile strength σ _a , psi	Strength-to-hardness ratio σ _a / HB	Tensile strength calculated by the above formula σ, psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ, psi		
Ref 7, p.767								
214	103000	481	107642	95.7	2,380	1,198,000	503	σ = 503 x HB
286	135000	472	143858	93.8				
381	185000	486	191643	96.5				
443	225000	508	222829	<u>99.0</u>				
512	260000	508	257536	99.1				
544	290000	533	273632	<u>94.4</u>				

* **Notice:** Brinell hardness numbers (HB) were obtained
by converting Rockwell hardness numbers (HRB and HRC) provided.

As can be seen from Tables 5.13A and 5.13B:

Linear regression formula provides 94.5 to 99.7% accuracy in calculating tensile strength

Statistical formula provides 94.4 to 99.0% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 210 to 545 HB

Appendix 5

Tensile strength of AISI Type L6 (UNS T61206) low-alloy special-purpose steel
versus Brinell hardness (3000-kgf applied load)

Table 5.14A. Linear regression formula for calculating tensile strength: $\sigma = 579 \times \text{HB} - 26083$

Brinell hardness HB*	Tensile strength, psi		Accuracy in calculating σ %	HB x σ_a	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a	calculated by the above formula, σ					slope	intercept	
Ref 7, p.767									
198	95000	88559	<u>93.2</u>	18810000	39204	9.025E+09	579	-26083	0.9959
302	140000	148775	94.1	42280000	91204	1.96E+10			
391	195000	200306	97.4	76245000	152881	3.803E+10			
431	230000	223466	97.2	99130000	185761	5.29E+10			
544	290000	288893	<u>99.6</u>	157760000	295936	8.41E+10			
1,866	950,000			394225000	764986	2.037E+11			

Table 5.14B. Statistical formula for calculating tensile strength: $\sigma = 509 \times \text{HB}$

Brinell hardness HB*	Tensile strength σ_a , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 7, p.767		σ_a / HB	σ , psi	%				
198	95000	480	100782	94.3	1,866	950,000	509	$\sigma = 509 \times \text{HB}$
302	140000	464	153718	<u>91.1</u>				
391	195000	499	199019	<u>98.0</u>				
431	230000	534	219379	95.4				
544	290000	533	276896	95.5				

* Notice: Brinell hardness numbers (HB) were obtained
by converting Rockwell hardness numbers (HRB and HRC) provided.

As can be seen from Tables 5.14A and 5.14B:

Linear regression formula provides 93.2 to 99.6% accuracy in calculating tensile strength

Statistical formula provides 91.1 to 98.0% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 195 to 545 HB

Appendix 5

Tensile strength of AISI Types H11 (UNS T20811) and H13 (UNS T20813) hot-work steels
versus Brinell hardness (3000-kgf applied load)

Table 5.15A. Linear regression formula for calculating tensile strength: $\sigma = 555 \times \text{HB} - 19290$

Brinell hardness HB*	Tensile strength, psi		Accuracy in calculating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a^{**}	calculated by the above formula, σ					slope	intercept	
Ref 8, p.461, Graph							555	-19290	0.9990
226	110000	106140	<u>96.5</u>	24860000	51076	1.21E+10			
253	121400	121125	99.8	30714200	64009	1.474E+10			
286	137300	139440	98.5	39267800	81796	1.885E+10			
327	158600	162195	97.8	51862200	106929	2.515E+10			
371	185200	186615	99.2	68709200	137641	3.43E+10			
421	214400	214365	<u>100</u>	90262400	177241	4.597E+10			
480	251600	247110	98.2	120768000	230400	6.33E+10			
560	290000	291510	99.5	162400000	313600	8.41E+10			
2,924	1,468,500			588843800	1162692	2.985E+11			

Table 5.15B. Statistical formula for calculating tensile strength: $\sigma = 502 \times \text{HB}$

Brinell hardness HB*	Tensile strength σ_a^{**} , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, p.461, Graph		σ_a / HB	σ , psi	%	HB	σ , psi	ratio σ / HB	$\sigma = 502 \times \text{HB}$
226	110000	487	113452	97.0	2,924	1,468,500	502	
253	121400	480	127006	<u>95.6</u>				
286	137300	480	143572	<u>95.6</u>				
327	158600	485	164154	96.6				
371	185200	499	186242	<u>99.4</u>				
421	214400	509	211342	98.6				
480	251600	524	240960	95.8				
560	290000	518	281120	96.9				

* Brinell hardness numbers (HB) were obtained
by converting Rockwell hardness HRC shown on the graph.

** Tensile strength values were determined from the graph.

As can be seen from Tables 5.15A and 5.15B:

Linear regression formula provides 96.5 to 100% accuracy in calculating tensile strength

Statistical formula provides 95.6 to 99.4% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 225 to 560 HB

Appendix 5

Tensile strength of AISI Type H12 (UNS T20812) hot-work steel
versus Brinell hardness (3000-kgf applied load)

Table 5.16A. Linear regression formula for calculating tensile strength: $\sigma = 616 \times \text{HB} - 41759$

Brinell hardness HB*	Tensile strength, psi		Accuracy in calculating σ %	HB x σ_a	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a^{**}	calculated by the above formula, σ					slope	intercept	
Ref 8, p.461, Graph							616	-41759	0.9951
226	104000	97457	<u>93.7</u>	23504000	51076	1.082E+10			
247	115900	110393	95.2	28627300	61009	1.343E+10			
272	127100	125793	99.0	34571200	73984	1.615E+10			
302	139800	144273	96.9	42219600	91204	1.954E+10			
336	157000	165217	95.0	52752000	112896	2.465E+10			
371	179500	186777	96.1	66594500	137641	3.222E+10			
411	208700	211417	98.7	85775700	168921	4.356E+10			
456	240500	239137	<u>99.4</u>	109668000	207936	5.784E+10			
512	281600	273633	97.2	144179200	262144	7.93E+10			
3,133	1,554,100			587891500	1166811	2.975E+11			

Table 5.16B. Statistical formula for calculating tensile strength: $\sigma = 496 \times \text{HB}$

Brinell hardness HB*	Tensile strength σ_a^{**} , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula σ , psi	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, p.461, Graph		σ_a / HB						
226	104000	460	112096	92.8	3,133	1,554,100	496	$\sigma = 496 \times \text{HB}$
247	115900	469	122512	94.6				
272	127100	467	134912	94.2				
302	139800	463	149792	93.3				
336	157000	467	166656	94.2				
371	179500	484	184016	97.5				
411	208700	508	203856	<u>97.7</u>				
456	240500	527	226176	94.0				
512	281600	550	253952	<u>90.2</u>				

* Brinell hardness numbers (HB) were obtained
by converting Rockwell hardness HRC shown on the graph.

** Tensile strength values were determined from the graph.

As can be seen from Tables 5.16A and 5.16B:

Linear regression formula provides 93.7 to 99.4% accuracy in calculating tensile strength

Statistical formula provides 90.2 to 97.7% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 225 to 515 HB

Appendix 5

Tensile strength of AISI Type H21 (UNS T20821) hot-work steels
versus Brinell hardness (3000-kgf applied load)

Table 5.17A. Linear regression formula for calculating tensile strength: $\sigma = 530 \times \text{HB} - 7144$

Brinell hardness HB*	Tensile strength, psi		Accuracy in calculating σ %	$\text{HB} \times \sigma_a$	$(\text{HB})^2$	σ_a^2	Parameters of the linear regression line		Correlation coefficient
	actual σ_a^{**}	calculated by the above formula, σ					slope	intercept	
Ref 8, p.462, Graph							530	-7144	0.9960
247	117100	123766	<u>94.6</u>	28923700	61009	1.371E+10			
272	136800	137016	<u>99.8</u>	37209600	73984	1.871E+10			
302	155300	152916	98.5	46900600	91204	2.412E+10			
336	175000	170936	97.7	58800000	112896	3.063E+10			
371	193400	189486	98.0	71751400	137641	3.74E+10			
411	213200	210686	98.8	87625200	168921	4.545E+10			
456	233700	234536	99.6	106567200	207936	5.462E+10			
480	242100	247256	97.9	116208000	230400	5.861E+10			
2,875	1,466,600			553985700	1083991	2.833E+11			

Table 5.17B. Statistical formula for calculating tensile strength: $\sigma = 510 \times \text{HB}$

Brinell hardness HB*	Tensile strength σ_a^{**} , psi	Strength-to-hardness ratio	Tensile strength calculated by the above formula	Accuracy in calculating σ %	Cumulative values:		Average strength-to-hardness ratio σ / HB	Formula for calculating tensile strength
					Brinell hardness HB	Tensile strength σ , psi		
Ref 8, p.461, Graph		σ_a / HB	σ , psi	%	HB	σ , psi	ratio σ / HB	strength
247	117100	474	125970	<u>93.0</u>	2,875	1,466,600	510	$\sigma = 510 \times \text{HB}$
272	136800	503	138720	98.6				
302	155300	514	154020	99.2				
336	175000	521	171360	97.9				
371	193400	521	189210	97.8				
411	213200	519	209610	98.3				
456	233700	513	232560	<u>99.5</u>				
480	242100	504	244800	98.9				

* Brinell hardness numbers (HB) were obtained
by converting Rockwell hardness HRC shown on the graph.

** Tensile strength values were determined from the graph.

As can be seen from Tables 5.17A and 5.17B:

Linear regression formula provides 94.6 to 99.8% accuracy in calculating tensile strength

Statistical formula provides 93.0 to 99.5% accuracy in calculating tensile strength

The use of the formulas is limited to Brinell hardness range of 245 to 480 HB