

ASM Ready Reference

Thermal Properties of Metals

ASM Materials Data Series

Prepared under the direction of the
ASM International Materials Properties Database Committee

Fran Cverna
Technical Editor



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Preface

This book is designed to serve the needs of the engineering and technical communities for high quality and comprehensive information regarding thermal properties of metals.

In 1997 the ASM International Materials Properties Database Committee sponsored and reviewed the *ASM Ready Reference: Properties & Units for Engineering Alloys*. The Committee recognized the need for consistency and equivalency, when integrating material property data from multiple sources into printed or electronic reference publications. The second book in the *Ready Reference* series applied the principles of consistency to selected electrical and magnetic properties of metals. This third book in the series continues integration from multiple sources for thermal properties of metals. The materials are sorted by a common materials hierarchy, and their property values are given in a consistent system of International Standard (SI) and customary units. The quality of the data and source of the data is also listed to enable the user to assess the data.

The book Chapters are broad categories of the major thermal properties covering thermal expansion, heat capacity, thermal conductivity, melt properties, and thermal emittance. Each chapter begins with a brief explanation of the property, derivation and conversion of the units used within, along with a discussion of other units that the reader may encounter. We trust this will be of benefit to the reader already familiar with the basics of thermal behavior. We do not attempt to present a textbook on thermodynamics in these brief introductions but seek to clarify possibly confusing terminology.

The first table of each Chapter summarizes values from low to high room temperature property value for major alloy groups. The subsequent data tables have the materials sorted by the material hierarchy. The complete hierarchy for materials found in this book is given in Table A.1 of the Appendix. As with the classification systems for materials in general use, the hierarchy is predominantly based on composition, but there are subdivisions that are application based.

Data Format

Data entries include the following:

- *Material name* may be a trade name, generic alloy, element, or description as assigned by a standards organization.
- *Temper* is listed as stated.
- *UNS number* is listed if known.
- *Property values in the preferred (SI) and alternate (customary) units.* The units used are those designated in the *ASM Ready Reference: Properties & Units for Engineering Alloys*. SI is the International System of Units (modernized Metric System). The customary units are English (lb. in.) units.
- *Qualifier* for the value. This is the qualifier as stated in the source of the data, such as typical, nominal, maximum. The most often used abbreviations are listed on the bottom of the page. The complete list is

given in the Appendix Table A.2. Often the source document will list the data as “not for design” or “for information only.” The “not for design” is applicable to all values listed, as there is no documented quality control process in place. It is therefore not listed on each record. If the value was derived from the information given in the source, such as conductivity derived from resistivity, or if units were converted, a “d” follows the value. Unit conversions that are merely a change in the value by a power of 10, are not labeled as derived. Values without the “d” are those most directly attributable to the source. A value can be established by definition, or by specification. There is still latitude as to how strictly the standard controls the material. It may be a mandatory or non-mandatory requirement, or one that is at the mutual consent of the buyer and seller.

- *Reference* to the data source listed in Table A.3 of the Appendix
- *Temperature* for which the value is valid is listed.
- *Notes* may include product forms, sizes, or processing information for which the value applies. Common uses of the alloy may be listed.

Limitations on the Use and Interpretation of Data

This book is intended to provide the materials engineer, scientist, or other specialist with a comparative listing of materials and their magnetic and electrical properties, to aid in the material selection process. Just as most of the sources listed bear the caveat “not for design,” the compilation of this data requires the same warning. Great effort has been expended to assure that the source material has been faithfully duplicated, but ASM International has no formal program whereby the validity of the data can be assured. The source references allow further investigation by the reader. It is the reader’s responsibility to take the prudent engineering and quality assurance steps necessary to assure that any material selected meets the design requirements.

Significant Figures

Individual sources have listed values to varied significant figures in the same data sets. The significant figures in values with trailing zeros (50,000), are not determined without more information. ASTM standards list sufficient decimal places to improve the accuracy of conversion and reconversion of the data. They stress that this does not imply the need to test the material to an accuracy beyond what the specification or the referenced test specification demands. For this reason, although the value has been listed to the same number of significant figures as the original when no derivation was required, no comparison should be made as to the precision of the values based on the significant figures shown. Values shown as “derived” have at least as many significant figures as the original source. As the conversion calculations were done in mass, significant figures were added to some values to assure that all had sufficient significant figures to preserve the original accuracy.

Availability of Materials

As it is often useful to have a source of data for historical materials, obsolete materials and materials listed by former trade names are included in the alloy field. No attempt was made to verify the commercial availability of materials.

Call for Future Action

A material database must be a dynamic creation, under constant revision. We at ASM International, who have the dissemination of materials information at the core of our vision statement, ask that qualified parties contribute material data to the Society for the betterment of the technical community. Your suggestions, corrections, and comments are welcome. They can be sent to the addresses found on the title page.

Fran Cverna
July 2002

Chapter 2

Thermal Expansion

THE COEFFICIENT OF LINEAR thermal expansion (CTE, α , or α_1) is a material property that is indicative of the extent to which a material expands upon heating. Different substances expand by different amounts. Over small temperature ranges, the thermal expansion of uniform linear objects is proportional to temperature change. Thermal expansion finds useful application in bimetallic strips for the construction of thermometers but can generate detrimental internal stress when a structural part is heated and kept at constant length.

For a more detailed discussion of thermal expansion including theory and the effect of crystal symmetry, the reader is referred to the CINDAS Data Series on Material Properties, Volumes 1 to 4, *Thermal Expansion of Solids* (Ref 1).

Definitions

Most solid materials expand upon heating and contract when cooled. The change in length with temperature for a solid material can be expressed as:

$$(l_f - l_0)/l_0 = \alpha_1 (T_f - T_0) \quad \Delta l/l_0 = \alpha_1 \Delta T$$

$$\alpha_1 = 1/l(d l/d T)$$

where l_0 and l_f represent, respectively, the original and final lengths with the temperature change from T_0 to T_f . The parameter α_1 CTE and has units of reciprocal temperature (K^{-1}) such as $\mu m/m \cdot K$ or $10^{-6}/K$. Conversion factors are:

To convert	To	Multiply by
$10^{-6}/K$	$10^{-6}/^{\circ}F$	0.55556
$10^{-6}/^{\circ}F$	$10^{-6}/K$	1.8
ppm/ $^{\circ}C$	$10^{-6}/K$	1
$10^{-6}/^{\circ}C$	$10^{-6}/K$	1
$(\mu m/m)/^{\circ}F$	$10^{-6}/K$	1.8
$(\mu m/m)/^{\circ}C$	$10^{-6}/K$	1
$10^{-6}/R$	$10^{-6}/K$	1.8

The coefficient of thermal expansion is also often defined as the fractional increase in length per unit rise in temperature. The exact definition

varies, depending on whether it is specified at a precise temperature (true coefficient of thermal expansion or $\bar{\alpha}$ or over a temperature range (mean coefficient of thermal expansion or α). The true coefficient is related to the slope of the tangent of the length versus temperature plot, while the mean coefficient is governed by the slope of the chord between two points on the curve. Variation in CTE values can occur according to the definition used. When α is constant over the temperature range then $\alpha = \bar{\alpha}$. Finite-element analysis (FEA) software such as NASTRAN (MSC Software) requires that α be input, not $\bar{\alpha}$.

Heating or cooling affects all the dimensions of a body of material, with a resultant change in volume. Volume changes may be determined from:

$$\Delta V/V_0 = \alpha_v \Delta T$$

where ΔV and V_0 are the volume change and original volume, respectively, and α_v represents the volume coefficient of thermal expansion. In many materials, the value of α_v is anisotropic; that is, it depends on the crystallographic direction along which it is measured. For materials in which the thermal expansion is isotropic, α_v is approximately $3\alpha_1$.

Measurement

To determine the thermal expansion coefficient, two physical quantities (displacement and temperature) must be measured on a sample that is undergoing a thermal cycle. Three of the main techniques used for CTE measurement are dilatometry, interferometry, and thermomechanical analysis. Optical imaging can also be used at extreme temperatures. X-ray diffraction can be used to study changes in the lattice parameter but may not correspond to bulk thermal expansion.

Dilatometry. Mechanical dilatometry techniques are widely used. With this technique, a specimen is heated in a furnace and displacement of the ends of the specimen are transmitted

to a sensor by means of push rods. The precision of the test is lower than that of interferometry, and the test is generally applicable to materials with CTE above $5 \times 10^{-6}/K$ ($2.8 \times 10^{-6}/^{\circ}F$) over the temperature range of -180 to $900^{\circ}C$ (-290 to $1650^{\circ}F$). Push rods may be of the vitreous silica type, the high-purity alumina type, or the isotropic graphite type. Alumina systems can extend the temperature range up to $1600^{\circ}C$ ($2900^{\circ}F$) and graphite systems up to $2500^{\circ}C$ ($4500^{\circ}F$). ASTM Test Method E 228 (Ref 2) covers the determination of linear thermal expansion of rigid solid materials using vitreous silica push rod or tube dilatometers.

Interferometry. With optical interference techniques, displacement of the specimen ends is measured in terms of the number of wavelengths of monochromatic light. Precision is significantly greater than with dilatometry, but because the technique relies on the optical reflectance of the specimen surface, interferometry is not used much above $700^{\circ}C$ ($1290^{\circ}F$). ASTM Test Method E 289 (Ref 3) provides a standard method for linear thermal expansion of rigid solids with interferometry that is applicable from -150 to $700^{\circ}C$ (-240 to $1290^{\circ}F$) and is more applicable to materials having low or negative CTE in the range of $<5 \times 10^{-6}/K$ ($2.8 \times 10^{-6}/^{\circ}F$) or where only limited lengths of thickness of other higher expansion coefficient materials are available.

Thermomechanical analysis measurements are made with a thermomechanical analyzer consisting of a specimen holder and a probe that transmits changes in length to a transducer that translates movements of the probe into an electrical signal. The apparatus also consists of a furnace for uniform heating, a temperature-sensing element, calipers, and a means of recording results. ASTM Test Method E 831 (Ref 4) describes the standard test method for linear thermal expansion of solid materials by thermomechanical analysis. The lower limit for CTE with this method is $5 \times 10^{-6}/K$ ($2.8 \times 10^{-6}/^{\circ}F$), but it may be used at lower or negative expansion levels with decreased accuracy and precision. The applicable temperature range is -120

to 600 °C (−185 to 1110 °F), but the temperature range may be extended depending on instrumentation and calibration materials.

Application Considerations

With respect to temperature, the magnitude of the CTE increases with rising temperature. Thermal expansion of pure metals has been well characterized up to their melting points, but data for engineering alloys at very high temperatures may be limited. In general, CTE values for metals fall between those of ceramics (lower values) and polymers (higher values). Common values for metals and alloys are in the range of 10 to $30 \times 10^{-6}/\text{K}$ (5.5 to $16.5 \times 10^{-6}/^\circ\text{F}$). The lowest expansion is found in the iron-nickel alloys such as Invar. Increasing expansion occurs with silicon, tungsten, titanium, silver, iron, nickel, steel, gold, copper, tin, magnesium, aluminum, zinc, lead, potassium, sodium, and lithium.

Low-expansion alloys are materials with dimensions that do not change appreciably with temperature. Alloys included in this category are various binary iron-nickel alloys and several ternary alloys of iron combined with nickel-chromium, nickel-cobalt, or cobalt-chromium alloying. Low-expansion alloys are used in applications such as rods and tapes for geodetic surveying, compensating pendulums and balance wheels for clocks and watches, moving parts that require control of expansion (such as pistons for some internal-combustion engines), bimetal strip, glass-to-metal seals, thermostatic strip, vessels and piping for storage and transportation of liquefied natural gas, superconducting systems in power transmissions, integrated-circuit lead frames, components for radios and other electronic devices, and structural components in optical and laser measuring systems.

Aluminum and Aluminum Alloys. The dimensional change of aluminum and its alloys with a change of temperature is roughly twice that of the ferrous metals. The average CTE for commercially pure metal is $24 \times 10^{-6}/\text{K}$ ($13 \times$

$10^{-6}/^\circ\text{F}$). Aluminum alloys are affected by the presence of silicon and copper, which reduce expansion, and magnesium, which increases it. Its high expansion should be considered when aluminum is used with other materials, especially in rigid structures, although the stresses developed are moderated by the low elastic modulus of aluminum. If dimensions are very large, as for example in a light alloy superstructure on a steel ship or where large pieces of aluminum are set on a steel framework or in masonry, then slip joints, plastic caulking, and other stress-relieving devices are usually needed. In the aluminum internal-combustion engine piston that works in an iron or steel cylinder, differential expansion is countered by the employment of low-expansion iron cylinder linings, or by split piston skirts and nonexpanding struts cast into the piston.

Steels. Plain chromium stainless steel grades have an expansion coefficient similar to carbon (mild) steels, but that of the austenitic grades is about $1\frac{1}{2}$ times higher. The combination of high expansion and low thermal conductivity means that precautions must be taken to avoid adverse effects. For example, during welding of austenitic grades use low heat input, dissipate heat by use of copper backing bars, and use adequate jiggling. Coefficient of thermal expansion must be considered in components that use a mixture of materials such as heat exchangers with mild steel shells and austenitic grade tubes.

Welding. The coefficient of thermal expansion is an important factor when welding two dissimilar base metals. Large differences in the CTE values of adjacent metals during cooling will induce tensile stress in one metal and compressive stress in the other. The metal subject to tensile stress may hot crack during welding, or it may cold crack in service unless the stresses are relieved thermally or mechanically. This factor is particularly important in joints that will operate at elevated temperatures in a cyclic temperature mode. A common example of this is austenitic stainless steel/ferritic steel pipe butt joints used in energy-conversion plants.

Data Tables

Table 2.1 lists ferrous and nonferrous metal and alloy groups in increasing order of CTE along with the range of CTE values from approximately room temperature to 100 °C (212 °F). Table 2.2 list CTE values for specific metals and alloys along with temperature, density, reference, and qualifying information where available. Table 2.2 is ordered according to material hierarchy. Refer to Appendix A.1 for a complete hierarchy.

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Table 2.1 Summary of Thermal Expansion

Coefficient of Linear Thermal Expansion (CTE), Approximate Ranges at Room Temperature to 100 °C (212 °F), from Lowest to Highest CTE Value

CTE			CTE		
10 ⁻⁶ /K	10 ⁻⁶ /°F	Material	10 ⁻⁶ /K	10 ⁻⁶ /°F	Material
2.6–3.3	1.4–1.8	Pure Silicon (Si)	12	6.5	Structural steel
2.2–6.1	1.2–3.4	Pure Osmium (Os)	11–13	5.9–7.1	Air-hardening medium-alloy cold work tool steel
4.5–4.6	2.5–2.6	Pure Tungsten (W)	11–13	6.2–7.0	High-manganese carbon steel
0.6–8.7	0.3–4.8	Iron-cobalt-nickel alloys	10–14	5.6–7.6	Malleable cast iron
4.8–5.1	2.7–2.8	Pure Molybdenum (Mo)	12	6.6	Mold tool steel
5.6	3.1	Pure Arsenic (As)	8.8–15	4.9–8.4	Nonresulfurized carbon steel
6.0	3.3	Pure Germanium (Ge)	11–14	5.9–7.5	Chromium molybdenum alloy steel
6.1	3.4	Pure Hafnium (Hf)	9.4–15	5.2–8.2	Chromium alloy steel
5.7–7.0	3.2–3.9	Pure Zirconium (Zr)	12–13	6.5–7.0	Molybdenum/molybdenum sulfide alloy steel
6.3–6.6	3.5–3.7	Pure Cerium (Ce)	12	6.8	Chromium vanadium alloy steel
6.2–6.7	3.4–3.7	Pure Rhenium (Re)	11–14	5.9–7.6	Cold work tool steel
6.5	3.6	Pure Tantalum (Ta)	11–14	6.0–7.5	Ductile medium-silicon cast iron
4.9–8.2	2.7–4.6	Pure Chromium (Cr)	7.6–17	4.2–9.4	Nickel with chromium and/or iron, molybdenum
6.8	3.8	Pure Iridium (Ir)	11–14	6.2–7.5	Resulfurized carbon steel
2.0–12	1.1–6.7	Magnetically soft iron alloys	12–13	6.4–7.4	High strength low-alloy steel (HSLA)
7.1	3.9	Pure Technetium (Tc)	4.8–20	2.7–11	Pure Lutetium (Lu)
7.2–7.3	4.0–4.1	Pure Niobium (Nb)	10–15	5.6–8.3	Duplex stainless steel
5.1–9.6	2.8–5.3	Pure Ruthenium (Ru)	9.9–13	5.5–7.3	High strength structural steel
4.5–11	2.5–6.2	Pure Praseodymium (Pr)	9.0–16	5.0–8.9	Pure Promethium (Pm)
7.1–9.7	3.9–5.4	Beta and near beta titanium	12–13	6.5–7.4	Pure Iron (Fe)
8.3–8.5	4.6–4.7	Pure Rhodium (Rh)	11–14	5.9–8.0	Metal matrix composite aluminum
8.3–8.4	4.6–4.7	Pure Vanadium (V)	10–15	5.6–8.6	Cobalt alloys (including Stellite)
5.5–11	3.1–6.3	Zirconium alloys	6.0–20	3.3–11	Pure Yttrium (Y)
8.4–8.6	4.7–4.8	Pure Titanium (Ti)	11–15	6.0–8.5	Gray cast iron
8.6–8.7	4.8–4.8	Mischmetal	9.0–17	5.0–9.6	Precipitation hardening stainless steel
7.6–9.9	4.2–5.5	Unalloyed or low-alloy titanium	13	7.4	Pure Bismuth (Bi)
7.7–10	4.3–5.7	Alpha beta titanium	7.0–20	3.9–11	Pure Holmium (Ho)
4.0–14	2.2–7.8	Molybdenum alloys	11–16	6.1–8.6	Nickel copper
8.8–9.1	4.9–5.1	Pure Platinum (Pt)	13	7.4	Pure Nickel (Ni)
7.6–11	4.2–5.9	Alpha and near alpha titanium	14	7.5	Palladium alloys
9.3–9.6	5.2–5.3	High-chromium gray cast iron	12–14	6.8–7.7	Pure Cobalt (Co)
9.3–9.9	5.2–5.5	Ductile high-chromium cast iron	10–17	5.6–9.6	Cast austenitic stainless steel
9.1–10	5.1–5.6	Pure Gadolinium (Gd)	13–15	7.0–8.2	Gold alloys
8.4–11	4.7–6.3	Pure Antimony (Sb)	8.1–19	4.5–11	High-nickel gray cast iron
8.6–11	4.8–6.3	Maraging steel	14	7.8	Bismuth tin alloys
9.9	5.5	Protactinium (Pa)	7.0–20	3.9–11	Pure Uranium (U)
9.8–10	5.4–5.8	Water-hardening tool steel	14	7.8	Pure Gold (Au)
10–11	5.6–5.9	Molybdenum high-speed tool steel	10–19	5.3–11	Pure Samarium (Sm)
6.8–14	3.8–7.8	Niobium alloys	7.9–21	4.4–12	Pure Erbium (Er)
9.3–12	5.2–6.5	Ferritic stainless steel	13–16	7.0–9.0	Nickel chromium silicon gray cast iron
7.6–14	4.2–7.5	Pure Neodymium (Nd)	14	7.8	Tungsten alloys
11	5.9	Cast ferritic stainless steel	14–15	7.7–8.4	Beryllium alloys
8.9–12	4.9–6.9	Hot work tool steel	12–18	6.7–10	Manganese alloy steel
9.5–12	5.3–6.6	Martensitic stainless steel	10–20	5.6–11	Iron alloys
9.9–12	5.5–6.5	Cast martensitic stainless steel	9.7–19	5.4–11	Proprietary alloy steel
11	6.1	Cermet	15	8.5	White cast iron
10–12	5.6–6.6	Ductile silicon-molybdenum cast iron	12–19	6.7–10	Austenitic cast iron with graphite
10–12	5.6–6.5	Iron carbon alloys	8.8–22	4.9–12	Pure Thulium (Tm)
9.3–12	5.2–6.9	Pure Terbium (Tb)	14–18	7.5–9.8	Wrought copper nickel
9.8–13	5.4–6.9	Cobalt chromium nickel tungsten	13–19	7.0–10	Ductile high-nickel cast iron
10–12	5.8–6.7	High-carbon high-chromium cold work tool steel	4.5–27	2.5–15	Pure Lanthanum (La)
11	6.2	Tungsten high-speed tool steel	16–18	8.8–10	Wrought high copper alloys
8.5–14	4.7–7.8	Commercially pure or low-alloy nickel	17	9.4	Cast high copper alloys
11	6.3	Low-alloy special purpose tool steel	15–19	8.3–11	Wrought bronze
7.1–16	3.9–8.7	Pure Dysprosium (Dy)	17–18	9.2–9.8	Cast copper
9.3–13	5.2–7.2	Nickel molybdenum alloy steel	16–18	9.1–10	Wrought copper
11–12	6.1–6.6	Pure Palladium (Pd)	17	9.6	Cast copper nickel silver
11	6.3	Pure Thorium (Th)	9.8–25	5.4–14	Austenitic stainless steel
11	6.4	Wrought iron	16–19	8.9–11	Cast bronze
10–13	5.7–7.0	Oil-hardening cold work tool steel	16–19	8.9–11	Wrought copper nickel silver
7.6–15	4.2–8.5	Pure Scandium (Sc)	18	10	Pure Barium (Ba)
11–12	6.1–6.8	Pure Beryllium (Be)	18	10	Cast copper nickel
6.3–17	3.5–9.4	Carbide	18	10	Pure Tellurium (Te)
10–13	5.7–7.3	Nickel chromium molybdenum alloy steel	18–20	9.9–11	Silver alloys
11–12	6.1–6.9	Shock-resisting tool steel			

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Table 2.1 Summary of Thermal Expansion

Coefficient of Linear Thermal Expansion (CTE), Approximate Ranges at Room Temperature to 100 °C (212 °F), from Lowest to Highest CTE Value

CTE			CTE		
10 ⁻⁶ /K	10 ⁻⁶ /°F	Material	10 ⁻⁶ /K	10 ⁻⁶ /°F	Material
19	11	Pure Silver (Ag)	25–26	14–15	Wrought magnesium aluminum zinc
17–21	9.4–12	Wrought brass	25–26	14–15	Cast magnesium aluminum manganese
16–23	8.9–13	3xx.x series cast aluminum silicon+copper or magnesium	26	15	Cast magnesium rare earth
16–24	8.9–13	2xxx series wrought aluminum copper	17–36	9.2–20	Commercially pure tin
16–24	8.9–13	Zinc copper titanium alloys	25–27	14–15	Commercially pure magnesium
16–24	9.1–13	6xxx series wrought aluminum magnesium silicon	26	15	Pure Ytterbium (Yb)
20	11	Pure Strontium (Sr)	20–33	11–18	Pure Indium (In)
20–21	11–12	Cast brass	25–28	14–16	Lead tin solder
18–24	10–13	1xx.x series commercially pure cast aluminum	27–29	15–16	Commercially pure or low-alloyed lead
20–22	11–12	4xx.x series cast aluminum silicon	28	16	Tin silver
19–23	11–13	2xx.x series cast aluminum copper	23–34	13–19	9xx.x series cast aluminum plus other elements
12–32	6.4–18	Pure Gallium (Ga)	29	16	Pure Lead (Pb)
22	12	Manganese (Mn)	28–30	16–17	Pure Thallium (Tl)
12–22	6.9–12	4xxx series wrought aluminum silicon	26–32	14–18	Magnesium alloys
22	12	Pure Calcium (Ca)	20–40	11–22	Unalloyed or low-alloy zinc
21–24	12–13	7xxx series wrought aluminum zinc	22–40	12–22	5xxx series wrought aluminum magnesium
22–24	12–13	3xxx series wrought aluminum manganese	30–32	17–18	Pure Cadmium (Cd)
23	13	8xx.x series cast aluminum tin	33–35	18–19	Zinc copper
23	13	Unalloyed aluminum ingot	35	19	Pure Europium (Eu)
22–25	12–14	1xxx series commercially pure wrought aluminum	37–49	21–27	Pure Selenium (Se)
23–25	13–14	5xx.x series cast aluminum magnesium	56	31	Pure Lithium (Li)
24–25	13–14	7xx.x series cast aluminum zinc	64	36	Pure Sulfur (S)
21–29	12–16	Tin lead	69–71	38–39	Pure Sodium (Na)
22–28	12–15	Zinc aluminum	83	46	Pure Potassium (K)
23–27	13–15	Zinc copper aluminum	90	50	Pure Rubidium (Rb)
25–26	14–15	Cast magnesium aluminum zinc	14–203	7.8–113	Pure Plutonium (Pu)
25–26	14–15	Pure Magnesium (Mg)	125	70	Pure Phosphorus (P)
			97–291	54–162	Pure Cesium (Cs)

Table 2.2 Coefficient of Linear Thermal Expansion (CTE) of Metals and Alloys

Temperature		Density		CTE		Notes	Reference
°C	°F	kg/m ³	lb/in. ³	10 ⁻⁶ /K	10 ⁻⁶ /°F		
Carbide based material							
71WC-12.5TiC-12TaC-4.5Co, Cobalt-bonded cemented carbide							
RT	RT	12000 u	0.434 d			Medium grain	16
200	390			5.2 u	2.9 d	Medium grain	16
1000	1830			6.5 u	3.6 d	Medium grain	16
72WC-8TiC-11.5TaC-8.5Co, Cobalt-bonded cemented carbide							
RT	RT	12600 u	0.455 d			Medium grain	16
200	390			5.8 u	3.2 d	Medium grain	16
1000	1830			6.8 u	3.8 d	Medium grain	16
75WC-25Co, Cobalt-bonded cemented carbide							
RT	RT	13000 u	0.470 d			Medium grain	16
200	390			6.3 u	3.5 d	Medium grain	16
84WC-16Co, Cobalt-bonded cemented carbide							
RT	RT	13900 u	0.502 d			Fine, coarse grain	16
200	390			5.8 u	3.2 d	Coarse grain	16
1000	1830			7.0 u	3.9 d	Coarse grain	16
90WC-10Co, Cobalt-bonded cemented carbide							
RT	RT	14500 u	0.524 d			Coarse grain	16
RT	RT	14600 u	0.527 d			Fine grain	16
200	390			5.2 u	2.9 d	Coarse grain	16
94WC-6Co, Cobalt-bonded cemented carbide							
RT	RT	15000 u	0.54 d			Fine, medium, coarse grain	16
200	390			4.3 u	2.4 d	Fine, medium, coarse grain	16
1000	1830			5.6 u	3.1 d	Coarse grain	16
1000	1830			5.9 u	3.3 d	Fine grain	16
1000	1830			5.4 u	3.0 d	Medium grain	16
97WC-3Co, Cobalt-bonded cemented carbide							
RT	RT	15300 u	0.553 d			Medium grain	16
200	390			4.0 u	2.2 d	Medium grain	16
Cr3C2							
RT	RT	6660 th	0.241 d	10.3 u	5.7 d		16
HfC							
RT	RT	12760 th	0.461 d	6.6 u	3.7 d		16
Mo2C							
RT	RT	9180 th	0.332 d	7.8 u	4.3 d		16
NbC							
RT	RT	7800 th	0.28 d	6.7 u	3.7 d		16
TaC							
RT	RT	14500 th	0.524 d	6.3 u	3.5 d		16
TiC							
RT	RT	4940 th	0.178 d	7.7 u	4.3 d		16
VC							
RT	RT	5710 th	0.206 d	7.2 u	4.0 d		16
ZrC							
RT	RT	6560 th	0.237 d	6.7 u	3.7 d		16
Cermet							
Cr-Al2O3, 77%Cr 23%Al2O3, Aluminum oxide cermet							
RT	RT	5900 u	0.21 u				16
25-800	77-1470			8.64 mean	4.80 mean		16
25-1000	75-1830			8.93 mean	4.96 mean		16
25-1315	77-2400			10.35 mean	5.75 mean		16
CrB-Cr-Mo, Boride-base cermet							
RT	RT	6770-7270 u	0.245-0.263 u				16
20-980	68-1800			9.90 mean	5.50 mean		16

RT, room temperature assumed if no temperature given; t, typical; d, derived; u, unstated; min, minimum; max, maximum. See Appendix for abbreviations and references.

Table 2.2 Coefficient of Linear Thermal Expansion (CTE) of Metals and Alloys

Temperature		Density		CTE		Notes	Reference
°C	°F	kg/m ³	lb/in. ³	10 ⁻⁶ /K	10 ⁻⁶ /°F		
Cermet							
CrB-Ni, Boride-base cermet							
RT	RT	6160-6270 u	0.223-0.225 u				16
20-980	68-1800			9.81 mean	5.45 mean		16
TiB2, Boride-base cermet							
RT	RT	4500 u	0.163 u				16
20-760	68-1400			6.39 mean	3.55 mean		16
Type A, Chromium carbide cermet							
RT	RT	7000 u	0.253 u	10.71 mean	5.95 mean		16
Type B, Chromium carbide cermet							
RT	RT	6900 u	0.250 u	11.10 mean	6.17 mean		16
ZrB2, Boride-base cermet							
RT	RT	6100 u	0.221 u				16
20-760	68-1400			7.5 mean	4.17 mean		16
ZrB2-B, Boride-base cermet							
RT	RT	4970-5270 u	0.180-0.191 u				16
20-1205	68-2200			5.76 u	3.20 u		16
Cast Iron, Austenitic with Graphite							
BS 3468-F1, Flake graphite							
RT	RT	7300 u	0.264 d	18.7 u	10.4 d		72
BS 3468-F2, Flake graphite							
RT	RT	7300 u	0.264 d	18.7 u	10.4 d		72
BS 3468-F3, Flake graphite							
RT	RT	7300 u	0.264 d	12.4 u	6.9 d		72
BS 3468-S2, Spheroidal graphite							
RT	RT	7400 u	0.267 d	18.7 u	10.4 d		72
BS 3468-S2B, Spheroidal graphite							
RT	RT	7400 u	0.267 d	18.7 u	10.4 d		72
BS 3468-S2C, Spheroidal graphite							
RT	RT	7400 u	0.267 d	18.4 u	10.2 d		72
BS 3468-S2M, Spheroidal graphite							
RT	RT	7400 u	0.267 d	14.7 u	8.2 d		72
BS 3468-S2W, Spheroidal graphite							
RT	RT	7400 u	0.267 d	18.7 u	10.4 d		72
BS 3468-S3, Spheroidal graphite							
RT	RT	7400 u	0.267 d	12.6 u	7.0 d		72
BS 3468-S5S, Spheroidal graphite							
RT	RT	7600 u	0.275 d	12.1 u	6.7 d		72
BS 3468-S6, Spheroidal graphite							
RT	RT	7300 u	0.264 d	18.2 u	10.1 d		72
Cast Iron, Ductile							
100-70-03							
RT	RT	7110 d	0.257 u				67
20-200	68-390			10.8 d	6.0 u		67
120-90-02							
RT	RT	7110 d	0.257 u				67
20-200	68-390			11.7 d	6.5 u		67
20-26% Ni							
20-200	68-390			4.0-18.9 d	2.2-10.5 u	Austenitic	67
60-40-18							
RT	RT	7110 d	0.257 u				67
20-200	68-390			11.9 d	6.6 u		67

RT, room temperature assumed if no temperature given; t, typical; d, derived; u, unstated; min, minimum; max, maximum. See Appendix for abbreviations and references.

Table 2.2 Coefficient of Linear Thermal Expansion (CTE) of Metals and Alloys

Temperature		Density		CTE		Notes	Reference
°C	°F	kg/m ³	lb/in. ³	10 ⁻⁶ /K	10 ⁻⁶ /°F		
Cast Iron, Ductile							
60-45-10							
20-100	68-212			11.5 d	6.4 u	Ferritic	67
20-200	68-390			11.7-11.9 d	6.5-6.6 u	Ferritic	67
20-600	68-1112			13.5 d	7.5 u	Ferritic	67
80-55-06							
RT	RT	7110 d	0.257 u				67
20-200	68-390			11.0 d	6.1 u		67
80-60-03							
20-100	68-212			11.5 d	6.4 u	Pearlitic	67
20-200	68-390			11.9-12.6 d	6.6-7.0 u	Pearlitic	67
20-300	68-570			12.6 d	7.0 u	Pearlitic	67
20-400	68-750			13.1 d	7.3 u	Pearlitic	67
20-500	68-930			13.3 d	7.4 u	Pearlitic	67
20-600	68-1112			13.5 d	7.5 u	Pearlitic	67
20-700	68-1292			13.9 d	7.7 u	Pearlitic	67
Ferritic ductile iron							
20-100	68-212			11.2 u	6.23 u		15
20-200	68-390			12.2 u	6.78 u		15
20-300	68-570			12.8 u	7.12 u		15
20-400	68-750			13.2 u	7.34 u		15
20-500	68-930			13.5 u	7.51 u		15
20-600	68-1110			13.7 u	7.62 u		15
20-700	68-1290			13.8 u	7.67 u		15
20-760	68-1400			14.8 u	8.23 u		15
20-870	68-1600			15.3 u	8.51 u		15
High-chromium cast iron (ferritic), Heat resistant							
RT	RT	7300-7500 u	0.264-0.271 u				15, 58
21	70			9.3-9.9 u	5.2-5.5 u		15, 58
High-nickel ductile (20% Ni) cast iron, Heat resistant							
RT	RT	7400 u	0.268 u				15, 58
21	70			18.7 u	10.4 u		15, 58
High-nickel ductile (23% Ni) cast iron, Heat resistant							
RT	RT	7400 u	0.268 u				15, 58
21	70			18.4 u	10.2 u		15, 58
High-nickel ductile (30% Ni) cast iron, Heat resistant							
RT	RT	7500 u	0.270 u				15
20-205	68-400			12.6-14.4 u	7.0-8.0 d		15
High-nickel ductile (36% Ni) cast iron, Heat resistant							
RT	RT	7700 u	0.278 u				15
20-205	68-400			7.2 u	4.0 d		15
High-nickel ductile cast iron, Corrosion-resistant							
RT	RT	7400 u	0.267 u				15, 58
21	70			12.6-18.7 u	7.0-10.4 d		15, 58
Medium silicon ductile iron							
RT	RT	7100 u	0.257 u				58, 72
21	70			10.8-13.5 u	6.0-7.5 u		58, 72
Medium-silicon ductile cast iron, Heat resistant							
RT	RT	7100 u	0.257 u				15
21	70			10.8-13.5 u	6.0-7.5 d		15
Ni-resist type D-2							
RT	RT	7418 u	0.268 u				57, 67
RT	RT			17.6 d	9.8 u		67
21-204	70-400			14.4 d	8.0 u		67

RT, room temperature assumed if no temperature given; t, typical; d, derived; u, unstated; min, minimum; max, maximum. See Appendix for abbreviations and references.

Table 2.2 Coefficient of Linear Thermal Expansion (CTE) of Metals and Alloys

Temperature		Density		CTE		Notes	Reference
°C	°F	kg/m ³	lb/in. ³	10 ⁻⁶ /K	10 ⁻⁶ /°F		
Cast Iron, Ductile							
Ni-resist type D-2B							
RT	RT	7474 u	0.270 u				67
20-200	68-390			18.7 d	10.4 u		67
Ni-resist type D-2C							
RT	RT	7418 u	0.268 u				67
20-200	68-390			18.4 d	10.2 u		67
Ni-resist type D-3							
RT	RT	7474 u	0.270 u	9.9 d	5.5 u		67
21-204	70-400			12.6 d	7.0 u		67
Ni-resist type D-4							
RT	RT	7474 u	0.270 u	13.1 d	7.3 u		67
21-204	70-400			18.7 d	10.4 u		67
Ni-resist type D-5							
RT	RT	7695 u	0.278 u	5.0 d	2.8 u		67
Pearlitic ductile iron							
20-100	68-212			10.6 u	5.89 u		15
20-200	68-390			11.7 u	6.51 u		15
20-300	68-570			12.4 u	6.89 u		15
20-400	68-750			13.0 u	7.23 u		15
20-500	68-930			13.3 u	7.39 u		15
20-600	68-1110			13.6 u	7.56 u		15
20-760	68-1400			14.8 u	8.23 u		15
20-870	68-1600			15.3 u	8.51 u		15
Silicon-molybdenum ductile iron							
RT	RT	6850 u	0.247 d	10.0-11.8 u	5.6-6.6 d		72
Cast Iron, Gray							
BS 1452 Grade 150							
RT	RT	7050 u	0.255 d				72
20-200	68-390			11.0 u	6.1 d		72
20-400	68-750			12.5 u	6.9 d		72
BS 1452 Grade 180							
RT	RT	7100 u	0.257 d				72
20-200	68-390			11.0 u	6.1 d		72
20-400	68-750			12.5 u	6.9 d		72
BS 1452 Grade 220							
RT	RT	7150 u	0.258 d				72
20-200	68-390			11.0 u	6.1 d		72
20-400	68-750			12.5 u	6.9 d		72
BS 1452 Grade 250							
RT	RT	7200 u	0.260 d				72
20-200	68-390			11.0 u	6.1 d		72
20-400	68-750			12.5 u	6.9 d		72
BS 1452 Grade 300							
RT	RT	7250 u	0.262 d				72
20-200	68-390			11.0 u	6.1 d		72
20-400	68-750			12.5 u	6.9 d		72
BS 1452 Grade 350							
RT	RT	7300 u	0.264 d				72
20-200	68-390			11.0 u	6.1 d		72
20-400	68-750			12.5 u	6.9 d		72
BS 1452 Grade 400							
RT	RT	7300 u	0.264 d				72
20-200	68-390			15.0 u	8.3 d	Acicular iron	72

RT, room temperature assumed if no temperature given; t, typical; d, derived; u, unstated; min, minimum; max, maximum. See Appendix for abbreviations and references.



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