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:

$$(l_f - l_0)/l_0 = \alpha_1 \, (T_f - T_0) \quad \Delta l/l_0 = \alpha_1 \Delta T$$
$$\alpha_1 = 1/l(dl/dT)$$

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 μm/m · K or 10^{-6}/K. Conversion factors are:

To convert	To	Multiply by
10^{-6}/K	10^{-6}/°F	0.55556
10^{-6}/°F	10^{-6}/K	1.8
ppm/°C	10^{-6}/K	1
10^{-6}/°C	10^{-6}/K	1
(μm/m)/°F	10^{-6}/K	1.8
(μm/m)/°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 5×10^{-6}/K (2.8×10^{-6}/°F) over the temperature range of –180 to 900 °C (–290 to 1650 °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 °C (2900 °F) and graphite systems up to 2500 °C (4500 °F). ASTM Test Method E 228 (Ref 2) cove 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 °C (1290 °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 °C (–240 to 1290 °F) and is more applicable to materials having low or negative CTE in the range of $<5 \times 10^{-6}$/K (2.8×10^{-6}/°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 5×10^{-6}/K (2.8×10^{-6}/°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 30×10^{-6}/K (5.5 to 16.5×10^{-6}/°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 24×10^{-6}/K (13×10^{-6}/°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 1½ 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 jigging. 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.

REFERENCES

1. R.E. Taylor, CINDAS Data Series on Materials Properties, *Thermal Expansion of Solids,* Vol 1–4, ASM International, 1998
2. "Standard Test Method for Linear Thermal Expansion of Solid Materials with a Vitreous Silica Dilatometer," E 228-95, *Annual Book of ASTM Standards,* ASTM, 1995
3. "Standard Test Method for Linear Thermal Expansion of Rigid Solids with Interferometry," E 289-99, *Annual Book of ASTM Standards,* ASTM, 1999
4. "Standard Test Method for Linear Thermal Expansion of Solid Materials by Thermomechanical Analysis," E 831, *Annual Book of ASTM Standards,* ASTM, 2000

SELECTED REFERENCES

- J.E. Eltherington & Son (Aluminium) Ltd, http://www.eltherington.co.uk/, 2002
- Interdisciplinary Research Centre in Computer Aided Materials Engineering, Materials Engineering Department, University of Wales, Swansea, U.K., http://irc.swansea.ac.uk/, 1998; revised 2001
- *Metals Handbook Desk Edition,* 2nd ed., ASM International, 1998
- R. Nave, Hyperphysics, Georgia State University, http://hyperphysics.phy-astr.gsu.edu, 2002
- *Welding, Brazing, and Soldering,* Vol 6, *ASM Handbook,* ASM International, 1993

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

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

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

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

Temperature		Density		CTE			
°C	°F	kg/m ^{3}	lb/in. ^{3}	10^{-6} /K	10^{-6}/ °F	Notes	Reference
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

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Publication title	Product code
ASM Ready Reference: Thermal Properties of Metals	06702G