Chapter 2

Thermal Expansion

THE COEFFICIENT OF LINEAR thermal expansion (CTE, \( \alpha \) or \( \alpha_v \)) 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 expansion including theory and the effect of

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:

\[ \Delta l = l_f - l_i = \alpha V \Delta T \]

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

<table>
<thead>
<tr>
<th>To convert</th>
<th>To</th>
<th>Multiply by</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 10^6/K )</td>
<td>( 10^6/\circ F )</td>
<td>0.55556</td>
</tr>
<tr>
<td>( 10^{-6}/\circ F )</td>
<td>( 10^{-6}/K )</td>
<td>1.8</td>
</tr>
<tr>
<td>ppm/\circ C</td>
<td>( 10^{-6}/K )</td>
<td>1</td>
</tr>
<tr>
<td>( 10^{-6}/\circ C )</td>
<td>( 10^{-6}/K )</td>
<td>1</td>
</tr>
<tr>
<td>( 10^{-6}/\circ F )</td>
<td>( 10^{-6}/K )</td>
<td>1.8</td>
</tr>
<tr>
<td>( 10^{-6}/\circ F )</td>
<td>( 10^{-6}/K )</td>
<td>1</td>
</tr>
<tr>
<td>( 10^{-6}/R )</td>
<td>( 10^{-6}/K )</td>
<td>1.8</td>
</tr>
</tbody>
</table>

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 \( \alpha \) or over a temperature range (mean coefficient of thermal expansion or \( \alpha \)). 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 \( \alpha \) is constant over the temperature range then \( \alpha = \alpha_\perp \).

Finite-element analysis (FEA) software such as NASTRAN (MSC Software) requires that \( \alpha \) be input, not \( \alpha_\perp \).

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 \( \Delta V \) and \( V_0 \) are the volume change and original volume, respectively, and \( \alpha_v \) represents the volume coefficient of thermal expansion. In many materials, the value of \( \alpha_v \) is anisotropic; that is, it depends on the crystallographic direction along which it is measured. For materials in which the thermal expansion is isotropic, \( \alpha_v \) is approximately 3\( \alpha_\perp \).

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 °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 289 (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 °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 \( (–240 \text{ to } 1290 °F) \) and is more applicable to materials having low or negative CTE in the range of \( <5 \times 10^{-6}/K \) \( (2.8 \times 10^{-6}/\circ F) \) 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
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


SELECTED REFERENCES

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