Electronics Materials-Coefficient of Thermal Expansion

The basis of CTE

Materials expand because an increase in temperature leads to greater thermal vibration of the atoms in a material, and hence to an increase in the average separation distance of adjacent atoms.

The linear coefficient of thermal expansion a (Greek letter alpha) describes by how much a material will expand for each degree of temperature increase, as given by the formula:

where:

$$\alpha = \frac{dl}{l \times dT}$$

dl = the change in length of material in the direction being measured

l = overall length of material in the direction being measured

dT = the change in temperature over which dl is measured

Although a ratio is dimensionless, expansion has the unit k−1, and is normally quoted in parts per million per °C rise in temperature. There is a related volume coefficient of thermal expansion, but the acronym CTE1 typically refers just to the linear expansion.

1 In some books you will find CTE referred to by the older (and less correct term) of TCE, or ‘Thermal (or Temperature) Coefficient of Expansion’.

CTE variation with materials

The magnitude of the CTE depends on the structure of the material. As can be visualized from Figure 1, the atoms would only stay at a constant separation at absolute zero; above that, their increasing thermal energy generates some movement about the mean, and the mean itself increases slightly because the bond energy curve has an asymmetric shape.

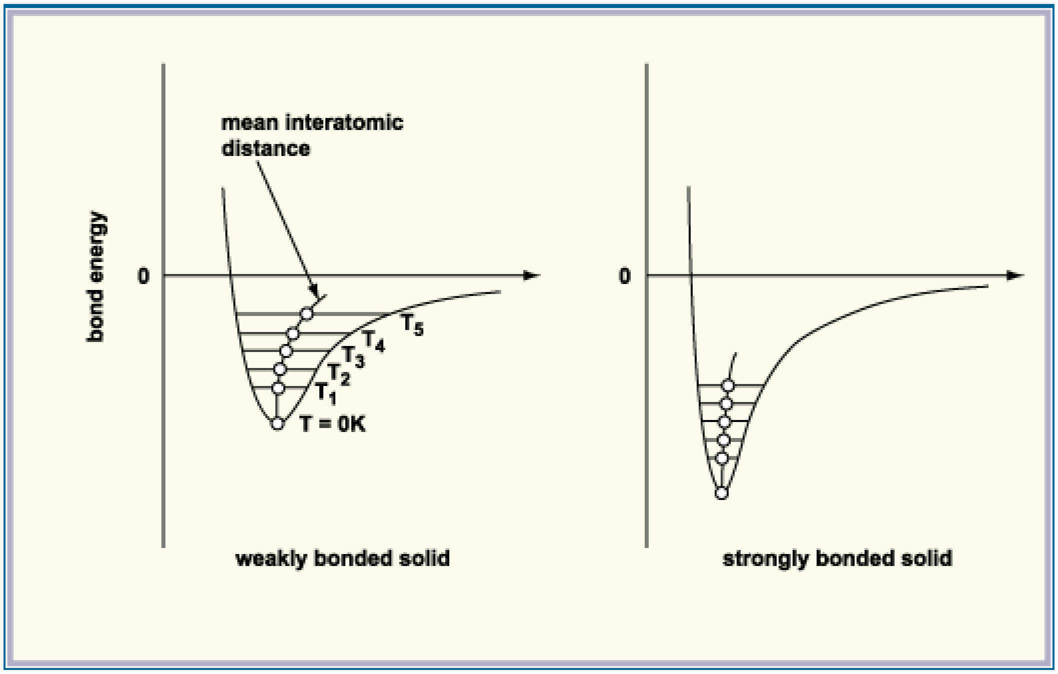

Figure 1: Plot of bonding energy against inter-atomic distance

Figure 1 also helps us to visualise why strongly-bonded insulators, such as ceramics have relatively low CTEs compared to metals, and why loosely-bonded structures such as polymers generally have high CTEs, especially those that are thermoplastics or elastomers.

Table 1 gives some examples of linear coefficients of thermal expansion for some of the materials we will be considering throughout this course.

Table 1: CTEs for some common electronic materials

material	CTE (ppm/°C)
silicon	3.2
alumina	6–7
copper	16.7
tin-lead solder	27
E-glass	54
S-glass	16
epoxy resins	15–100
silicone resins	30–300

It is important to realise that:

- The CTE is often not the same in all axes (that is, not 'isotropic'). In PCB laminates, for example, the values are different in the plane of the board (X-Y) and through its thickness (Z).
- The CTE is rarely linear and should be quoted either at a specific temperature or as an average over a given temperature range.
- The variation in CTE with temperature is only a fairly smooth function if the material is undergoing no phase transitions. For example, with thermosets, there is a marked increase in CTE above the glass transition temperature.

Measuring CTE

With typical CTEs in the range 5-50 ppm/K, the changes in dimensions are extremely small. The proverbial 'six-inch rule', with a CTE of 11 ppm/K, will expand by only 1.65µm for each degree of temperature rise: this corresponds to only a few wavelengths of light. As such small changes in length are difficult to measure, early data tended to make measurements of the average CTE between two fixed temperatures, say 25°C and 300°C.

Although making accurate measurements is still beyond the scope of the average laboratory, CTEs are nowadays typically measured by interferometry, which looks at the changes in the interference pattern of monochromatic light, usually from a laser. You will find a description of this technique at http://www.pmiclab.com/testing/ThermalExpansion.html.

With this technique it is possible to plot strain against temperature throughout a heating or cooling cycle. The slope of the strain/temperature curve at a given temperature is the instantaneous coefficient of thermal expansion. Of course, to give comparisons with earlier figures, the average slope over a temperature range can also be derived from the data.

Implications for composite assemblies

It is tempting to think of such small CTE figures as meaningless for our purposes, until that is you remember the bimetallic strip experiment that you probably carried out at school. This uses a strip made of two different strips of metal, typically brass and steel, which are sandwiched together. Though straight at the temperature at which they were joined together (usually room temperature) the strip bends quite dramatically when place in a flame or in a dewar flask of liquid nitrogen, but returns to its rest state when the source of heat or cold is removed. This principle is used in applications such as cooker and fridge thermostats .

Most structures that you will design have materials with different CTEs sandwiched together or soldered/bolted on. When temperature excursions occur, because of changes in either ambient conditions or the power dissipated by the circuit, these materials will expand differently, leading to the creation of stresses. In severe cases, we may get warping of an entire board, or solder joint fracture. These are issues to which we will return in Failure mechanisms.

Author: Martin Tarr

Source: http://www.ami.ac.uk/courses/topics/0197_cte/index.html