Temperature and Dimensional Measurement

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Temperature and Dimensional Measurement is a short tutorial on the effects of temperature on dimensional measurements.

Everything changes size when the temperature changes. This is a common phenomenon, although the changes are usually too small to see. Expansion joints in bridges, to allow for seasonal variations in the length of the bridge span, being one of the more noticeable examples.

In industrial measurement, small differences in size are much more critical, and thus small changes that we normally do not notice become important.

Thermal Expansion

When a material is heated the distance between individual atoms will change. For most materials the atoms get, on average, further apart (although there are some exceptions). Since the change is the same for all atoms, the total length change depends on how many atoms are in the length. This makes the length change proportional to length. You would expect this, of course; if a 1 meter piece of metal changes length by some small amount, a two meter piece would be expected to change by twice the amount.

Also, for small changes in temperature the length change is proportional to the temperature change. The constant of proportionality is called the coefficient of thermal expansion, denoted by the Greek letter alpha (α). This coefficient is not really constant over large temperature ranges, which as we will see later, can cause problems.

$$\frac{\Delta \mathbf{L}}{\mathbf{L}} = \alpha[\Delta \mathbf{T}]$$

ΔL = Change in Length

ΔT = Change in Temperature

α = Coefficient of Thermal Expansion (CTE)

20 Degrees as Reference Temperature

Since all matter changes size with temperature, in order to define the size of something we must also say at what temperature it is the stated size. The international standard temperature for dimensional measurements is standardized in ISO 1 as 20 degrees Celsius (°C). The statement above is from the US tolerancing standard, and shows that all drawings that have dimension marked on them, by default, refer the to dimensions at 20°C.

ASME/ANSI Y14.5M
Dimensioning and Tolerancing

1.4 Fundamental Rules

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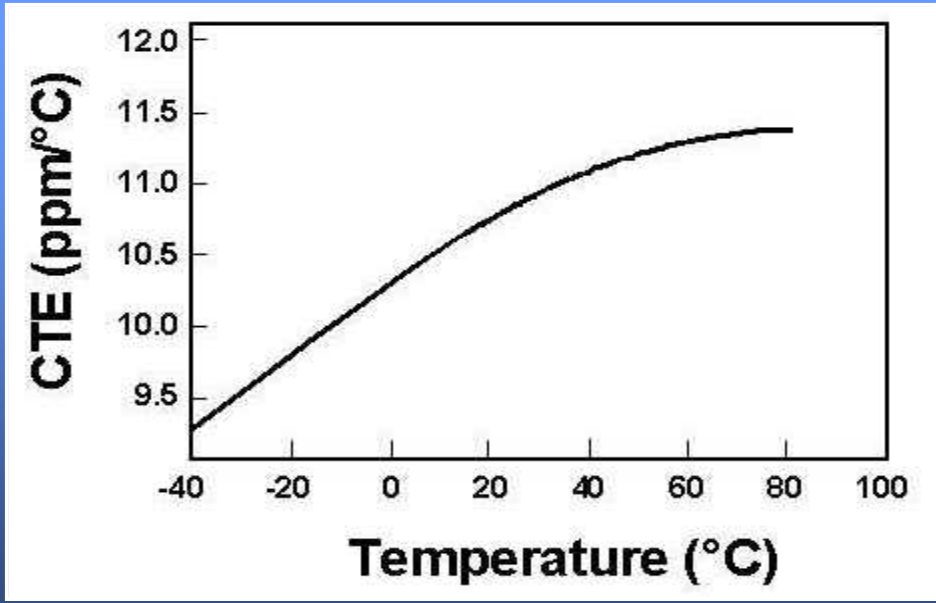
(k) Unless otherwise specified, all dimensions are applicable at 20 °C (68 °F). Compensation may be made for measurements made at other temperatures.

Gage Block CTE

The diagram shows a typical coefficient of thermal expansion. While it does not change tremendously as the temperature changes, it does change enough that the details would need to be known for very accurate measurement.

The ASME B89.1.9 Gage Block Standard says that steel gage blocks should have a CTE between 10.5-12.5 ppm/°C at 20°C. This block satisfies this criteria, but over a few degrees the CTE will change by a few per cent.

Calibration laboratories address the problem by keeping the lab temperature very near 20°C, the lab at NIST stays within 0.1°C of 20°C at all times, making corrections for thermal expansion so small as to be negligible. This strategy is not possible in most factories, where temperature variations of 5-10°C may occur.



CTE of Typical Materials

The table shows some common materials, and their response to temperature change. These are average numbers for the CTE, as we shall see later there are many different materials going by these names, with different values for the CTE.

The last column is meant to give you a rough "ballpark" estimate of the importance of the temperature in measurements. A length measurement with an uncertainty of 1 ppm (1 microinch/inch) is a very high accuracy measurement. For steel, if I do not know the temperature of the part better than 0.09°C (0.16°F) the uncertainty of my measurement is uncertain by 1 ppm just from the temperature uncertainty. For aluminum, the problem is twice as bad. For fused quartz the temperature does not matter much.

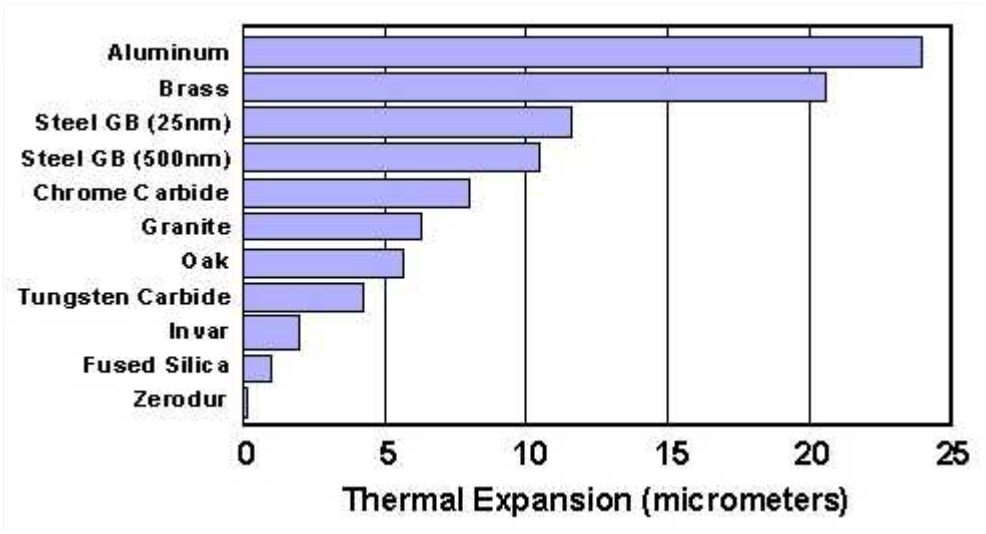
Material	CTE (ppm/K)	T needed for 1 ppm Change
Steel	11.5	0.09
Brass	21	0.05
Aluminum	24	0.04
Glass	3-7	0.2
Invar	1.2	0.9
Zerodur	0.05	20
Quartz	0.5	1.8
Granite	6.3	0.16

5 °C Expansion of 100 mm Samples

Here is another example of how to think of thermal expansion. If we have a 100 mm (4 in) long sample of each of these materials, and change the temperature 5°C (9°F), the lengths will change as shown.

Twenty-five micrometers is about 0.001 inch. As you can see, the question "How close should my lab temperature be to 20°C be?" depends a great deal upon what you are going to measure.

Note also there are two values for steel gage blocks (Steel GB) in the chart. One of the peculiarities of most steel gage blocks is that the CTE depends on the length of the block. We will discuss this more later.



Thermal Effects on Gage Blocks

NIST has two sets of master long steel gage blocks. The CTE for each block was measured, giving the results in the table. There are two things to notice. First, Even though the blocks are from the same manufacturer, the CTE can be different from block to block by more than a few percent. Thus, even for gage blocks you cannot be sure of the CTE by better than a few percent unless the block is measured.

Second, the CTE gets smaller as the block gets longer. These blocks are made from AISI 52100 steel, and the ends are hardened. It turns out that the CTE for the hardened steel is about 12 ppm/°C and unhardened is about 10.5 ppm/°C. Only the first few centimeters on each end are hardened, so as the block gets longer the percentage of hardened length decreases.

Length (inch)	GB-1 CTE (ppm/°C)	GB-2 CTE (ppm/°C)	Range	Deviation from 11.5 ppm/°C
1	11.90	11.63	0.27	0.27
2	11.78	11.69	0.09	0.23
3	12.00	11.74	0.26	0.37
4	12.00	11.63	0.38	0.31
5	11.40	11.27	0.13	-0.16
6	11.25	11.23	0.08	-0.20
7	11.06	11.36	0.30	-0.29
8	11.22	10.92	0.30	-0.43
10	10.84	10.64	0.20	-0.76
12	10.71	10.64	0.07	-.082
16	10.80	10.58	0.22	-0.81
20	10.64	10.77	0.13	-0.80

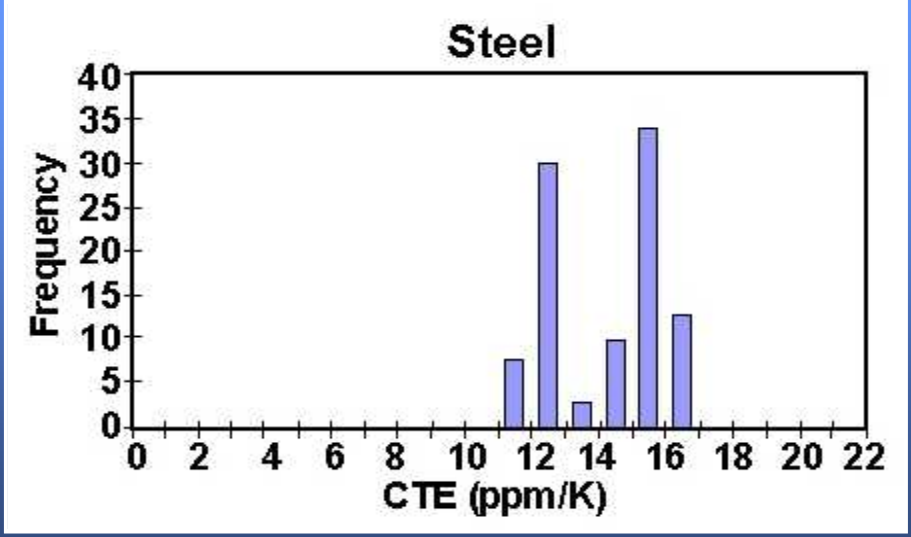
CTE for Steels

This is a compilation of the CTE's of a hundred or so different steels.

As you can see the normal gage block steel, at 11.5 ppm/°C is somewhat on the low end of the distribution.

The question here is, if you are given a part and told it is steel, what do you choose at the CTE. If "steel" is all you know, the best bet would be about 14 ppm/°C and the uncertainty would be about ±3 ppm/°C.

For high accuracy parts this would be a serious drawback. Of course, you would have to get in touch with someone who could tell you which type of steel you were measuring. That might help, although not as much as you might think.

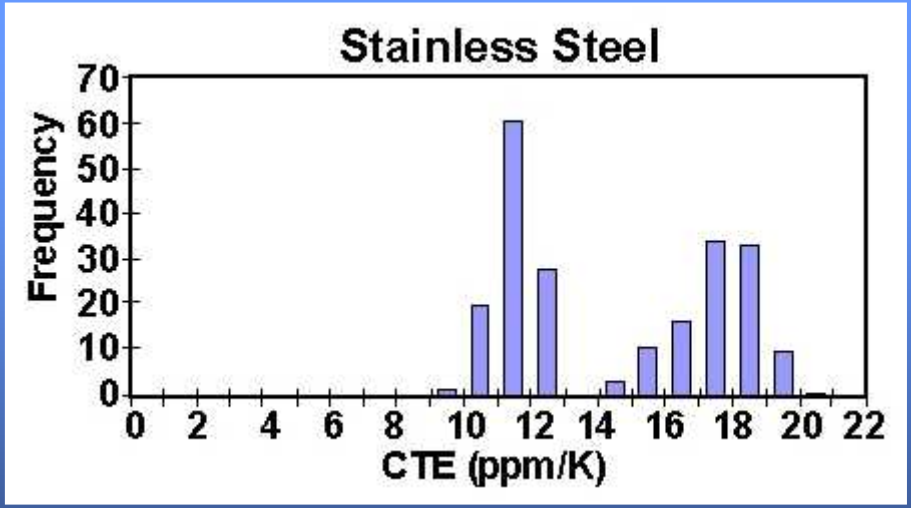


CTE for Stainless Steels

Here is a histogram of the CTE's for a large number of stainless steels. The most obvious characteristic is that the distribution has two distinct peaks.

The CTE for 300 series stainless steel runs in the 14 to 19 ppm/°C range, while that of 400 series stainless steel is between 10 and 12 ppm/°C.

Thus it is critically important to know the type of stainless you are using; the bias between the two main types of steel being nearly 50%.



CTE for Glass

This is a particularly interesting graph. Often we are asked to calibrate master grids or scale for use in precision optical measuring systems. The scales or grid plates are obviously glass, and often that is all of the information the owner has.

It is obvious from the graph that the word "glass" conveys almost no information about the CTE of the gage.

The best estimate is somewhere between 0 and 10 ppm/°C, with a correction of 5 ppm/°C applied to the data. Even if the artifact is calibrated the a precision environment of a national calibration laboratory, who will measure very near 20°C to minimize the uncertainty from thermal expansion, the customer will probably not have the temperature control to use the artifact at an uncertainty anywhere near that stated on the calibration report.

Reference Values

Next is the question of where to get the value of the CTE for a specific material. There are a large number of reference books that give values for the CTE, and a number of WEB sites that are useful. At the end of this tutorial we have made a list of sources that can be helpful.

There are 2 problems with most, if not all sources, of reference data.

First, there is no estimate of the uncertainty of the values in the tables. This includes the uncertainty of the measurement as well as the batch to batch variation in a given material. Even fairly well defined materials, such as ANSI numbered steels, still have ranges of the various components in the material. Luckily, most heat treatments do not change the CTE radically, but there are very few sources that provide data to help us with that conclusion.

Secondly, nearly all tables give the CTE as the average over some temperature range. In many cases you have to read the tables and footnotes carefully to find the applicable temperature range. An example of the problems in this area is shown in the next page.

Variations in Reported Values of the CTE

This table gives the CTE for AISI 1050 steel taken from three different sources. The CTE has been converted to ppm/°C, and the temperature ranges to °C as needed. Obviously the CTE changes with temperature, and this leads to different "average" values over different temperature ranges. Of course even the word "average" may be defined differently by the three sources.

The question is now, what is the CTE at 20°C?

This particular example is one for which multiple, seemingly independent sources exist. For most gages we do not even have this much information.

Reference	CTE	T-Range	CTE	T-Range	CTE	T-range
1	14.6	21-650				
2	11.5	20-100	13.5	25-200		
3	11.2	0-100	12.1	0-200	13.5	0-400

Summary

1. All materials change size with temperature change, and over small temperature changes the relative size change ($\Delta L/L$) is proportional to the temperature change, and the proportionality constant is the Coefficient of Thermal Expansion (CTE).
2. The CTE is very dependent on the details of the makeup of the material. Generic terms like "steel" or "ceramic" are virtually useless.
3. Given the exact type of material (e.g. AISI 52100 Steel) the CTE can be looked up in reference books, or sometimes obtained from the manufacturer. The uncertainty of the number is generally not available.
4. Reference books and manufacturers generally have the average CTE over some temperature range. Often the range contains the dimensional reference temperature of 20°C, but the value at 20°C is seldom available. Book values generally are the average over at least 80°C, and often 3 or 4 times as much. Since most metals have CTE that rise with temperature, an average CTE for 20-100°C is generally biased if used at room temperature. This bias is typically a few percent, but using an average CTE over larger temperature ranges can result in biases of 10% or more.

CTE for Some Common Materials

Material	CTE[1]	Material	CTE[1]
Alumina, Grade 99	7.8	Granite	6.3[2]
Aluminum Alloy 5086	23.7	Invar	1.2
Aluminum Alloy 6061	23.4	Sapphire (Aluminum Oxide - Al2O3)	4.0
Beryllium Copper	18	Stainless Steel, 304	17.3
Beryllium I-70H, Optical Grade	11.4	Stainless Steel, 316	16.0
Borosilicate Glass	4[2]	Stainless Steel, 440	10.2
Cast Iron, Gray	10.8[2]	Tool Steel, 52100	11.9
Chromium Carbide	8.4	Tool Steel, D2	10.5
Copper alloy, Free Cutting Brass	20.5	Tungsten Carbide (6% Cobalt Binder)	4.9
Copper Alloy, Yellow Brass	20.3	Zerodur	0.05
Copper, UNS C14310	17	Zirconia, 5-10% CaO Stabilized	7.5
Diamond, Natural	1.2	Zirconia, Gauge Block	9.2
Fused Silica, Fused Quartz	0.55	Zirconia, Y2O3 Stabilized	10.5

NOTES:

1. These are average values culled from a number of sources. They are, in general, averages over the range 0-100 °C, and the uncertainty is estimated to be 3-5% (k=2).
2. These entries are averages of a class of materials, and the variability within the class is over 10%.

Reference Material

Sources for CTE Data:

- MatWeb: Online Material Information Resource
  http://www.matweb.com
- eFunda Engineering Fundamentals: Properties of Common Solid Materials
  http://www.efunda.com/materials/common_matl/common_matl.cfm
- Comparisons of Materials: Coefficient of Thermal Expansion
  http://www.handyharmancanada.com/TheBrazingBook/comparis.htm
- Rembar: Technical Data on Metals
  http://www.rembar.com/tech2.htm