APRIL 2018 ISSUE #112

MATERION

TECHNICALTIDBITS

MATERION PERFORMANCE ALLOYS

Not talking about waistlines! - A brief discussion on thermal expansion.

- Coefficient of Thermal Expansion (a or CTE)
- Thermal Strain
- Coefficient of Linear Thermal Expansion
- Coefficient of Area Expansion
- Coefficient of Volume Expansion
- Isotropic Materials
- Low Expansion Alloys
- CTE-Matched Alloys

This next issue of Technical Tidbits will discuss thermal fatigue and thermal shock.

THERMAL EXPANSION **AND CONTRACTION**

The **coefficient of thermal expansion** (**a**), often abbreviated **CTE**, provides a measure of how much a material expands or shrinks when heated or cooled. Its units are expressed in strain per time, which becomes reciprocal seconds (s^{-1}). The equation for calculating the change in length (ΔL) of a component of length (L) due to a change in temperature (ΔT) is $\Delta L = L \cdot \alpha \cdot \Delta T$. Rearranging, since the change in length divided by the original length is strain, thermal strain can be calculated as: $\varepsilon_{thermal} = \frac{\Delta L}{L} = \alpha \cdot \Delta T$.

Strictly speaking, the **coefficient of thermal expansion** described above deals with expansion in one direction only. Therefore, sometimes you will see this written as the coefficient of linear thermal expansion. The **coefficient of area expansion** and the **coefficient of volume expansion** describe change in area per degree temperature rise and the change in volume per degree temperature rise, respectively. For isotropic materials, these values are respectively twice and three times the linear coefficient of thermal expansion: $\frac{\Delta A}{A} = 2 \cdot \alpha \cdot \Delta T$ Again, it is important to note that this is for isotropic (non-directional) solid materials only, which means that their properties are the same in all directions. However, the value reported on solid material's data sheet will almost always be the linear expansion coefficient, unless otherwise noted. (There may be more than one value reported, particularly for composite materials where the rate of expansion may be different in different directions.)

Thermal strain expands in all three directions vs. mechanical strain which expands in one direction and contracts in the other two. 20% thermal strain would make a part 20% longer, thicker and wider. 20% mechanical strain would make a part 20% longer, but 6% narrower and thinner, assuming a Poisson's ratio of 0.3 (typical for most metals).

Like many other properties, the thermal expansion coefficient is not a constant, but instead is a function of temperature, as shown in Figure 1. Therefore, to accurately determine the thermal expansion and thermal strain, you will need to know not only the change in temperature, but what the starting temperature and ending temperature actually are, so you can use the proper value for CTE.

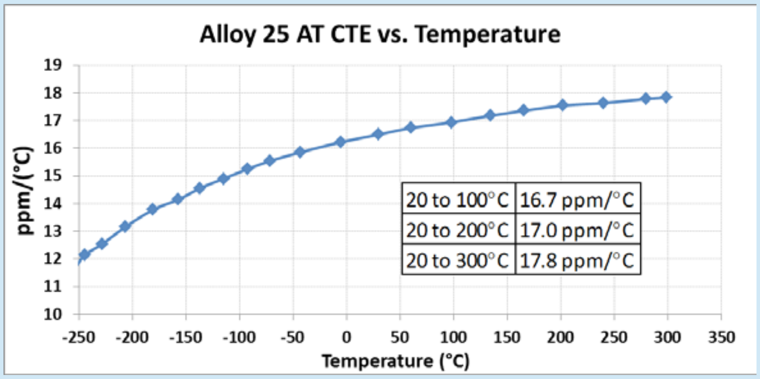

Figure 1. Two Different Methods of Presenting Thermal Expansion Data. You could plot a curve of instantaneous CTE vs temperature, as shown graphically above. Essentially, this a plot of the instantaneous slope of the thermal strain vs. temperature curve. The other means would be to present a table of linear expansion rates to be used in a particular range of temperatures, as shown in the inset.

THERMAL EXPANSION **AND CONTRACTION** (CONTINUED)

The CTE does have practical implications. For example, you can use known expansion vs. temperature behavior to construct a simple temperature gauge. Bimetallic sensors and switches make use of two materials with different thermal expansion rates bonded together. Since the two materials expand at different rates, the composite will curve toward the shorter (less expanded or more contracted side), which is useful for temperature gauges or to simply activate or deactivate an electric circuit when the temperature goes beyond certain limits.

There are also alloys that are specially designed to have low thermal expansion coefficients. The most well-known of these **low expansion alloys** is FeNi36, also known by the tradename Invar®. (The current holder of this trademark is Aperam Alloys Imphy Joint Stock Company France.) Near room temperature, this alloy has a CTE an order of magnitude lower than most metals, as shown in table 1.

Other alloys have CTE's that are matched to other materials. For example, Alloy 42 (FeNi42) and the FeNi29Co17 alloy known as Kovar® (currently a trademark of the Carpenter Technology Corporation of CRS Holdings, Inc.) have thermal expansion coefficients that are matched to glass and ceramic materials. This makes them ideal for hermetically sealed processor or sensor packages, where it is important to remain sealed no matter how hot or cold the package gets. A differential thermal expansion could easily break such a seal, so **CTE-matched alloys** are usually used here.

	20-100° C	20-300° C		20-100° C	20-300° C		20-100° C	20-300° C
Alloy 25 CuBe	16.7	17.8	Alloy 42	5.3	6.1	301 Stainless Steel	16.9	17.1
C11000 Cu	16.8	17.6	Kovar	5.8	5.2	316 Stainless Steel	16.0	16.2
C26000 Brass		20.0	Invar	1.2	3.8	430 Stainless Steel	10.4	11.0
C52100 Phosphor Bronze		18.2	Nickel 201	13.1	14.4	A91000 Al	23.1	25.4
C72900 CuNiSn		16.4	Monel ®400	13.9	15.5	R50250 Ti	8.5	9.2
Z13004 Zn	26	30.1	Inconel® 600	13.3	15.8	Ti6Al4V	8.6	9.2

Figure 1. Coefficient of Thermal Expansion for Various Metals at 20-300°C. The above are in ppm/°C. Monel and Inconel are registered trademarks of Special Metals Corporation.

Under certain conditions, the coefficient of thermal expansion can be negative. For example, between 0°C and 4°C, water will expand as it cools and contract as it warms. There are certain other compounds that show negative thermal expansion coefficients over wide temperature ranges such as cubic zirconium tungstenate (ZrW_2O_8). There are also some artificially constructed metamaterials that show this behavior as well.

The thermal expansion coefficient provides useful information for a number of applications, although it is another property that varies with temperature. In order to do meaningful calculations, you will need to know the coefficient that is appropriate for the temperature range you are working in. There is plenty of information available in the public literature that will help you choose the material that is best suited for your particular expansion problem.

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References:

"Alloy Performance Guide" © 2011 Materion Technical Materials.

ASTM E228-17, "Standard Test Method for Linear Thermal Expansion of Solid Materials With a Push-Rod Dilatometer" ASTM International, West Conshohocken, PA, 2017, www.astm.org

ASTM E831-14 "Standard Test Method for Linear Thermal Expansion of Solid Materials by Thermomechanical Analysis"ASTM International, West Conshohocken, PA, 2014, www.astm.org

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