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High-Resolution Methods for Measuring the Thermal Expansion Coefficient of Aerospace Materials

Gregory Wallace, William Speer, J. Ogren, and Omar S. Es-Said

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Accurately predicting the coefficient of thermal expansion for many aerospace components is critical to ensure proper functionality on orbit where the temperature gradient across a spacecraft can vary from +300 °F to –450 °F. Under these conditions, the linear approximations generated by theoretical equations no longer hold true, and experimental methods are needed. Although several methods exist for measuring the coefficient of thermal expansion of materials, laser interferometry yields high-resolution results, and the technique is widely accepted in the scientific community.

Keywords coefficient of thermal expansion (CTE), cryogenic, experimental methods, extreme temperatures, isotropic, material properties

1. Introduction

Materials that are used for aerospace applications are required to withstand temperatures that range from approximately +300 °F to –450 °F. Designing structures that need to survive extreme temperature differentials like this is often challenging for engineers. Many times, the structure is supporting critically aligned mirrors or antennas that require geometric stability for proper alignment. Temperature changes of this magnitude can severely distort structural components if materials with too high of coefficient of thermal expansion (CTE) are used. Additionally, large temperature gradients cause extremely high thermal stresses in the adhesively bonded joints that often connect structural members. Due to these issues, accurately predicting the CTE for aerospace materials over a broad temperature range is essential for mission success. Unfortunately, calculating the CTE under these conditions is not a trivial task.

2. Background

Most solid bodies expand as their temperature rises. As the temperature rises, an increase in energy causes the body's atoms (or molecules) to vibrate at higher amplitudes, thus creating an increase in the average separation between the material's atoms and an increase in the overall size of the solid (Ref 1). Conversely, when a solid body is cooled the energy decreases, which reduces the amplitude of vibration and causes the material to shrink. The property that relates a material's linear growth to its thermal environment is known as the average coefficient of linear expansion. The equation that describes this phenomenon is as follows (Ref 1):

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$$\Delta L = \alpha L \Delta T$$

where ΔL is the change in length due to a temperature differential, α is the average coefficient of linear expansion, L is the length of the sample at the initial temperature, and ΔT is the magnitude of the temperature differential.

Additionally, for isotropic solids (e.g., materials with linear expansion properties that are the same in all directions), the following equation can be used to predict volume changes due to temperature changes (Ref 1):

$$\Delta V = 3\alpha V \Delta T$$

where ΔV is the change in volume due to a temperature differential, α is the average coefficient of linear expansion, V is the volume of the sample at the initial temperature, and ΔT is the magnitude of the temperature differential.

Unfortunately, the average coefficient of linear expansion shown in the previous two expressions is an average value used for a given temperature range. The actual value for most materials varies with temperature; therefore, it is accurate only for a fairly small temperature differential (Ref 1). To make matters even more complicated, at extreme temperatures, such as those experienced in space missions, this material property ceases to behave linearly and it begins to follow a complex polynomial pattern (Ref 2). To accurately predict the thermal expansion of aerospace components that experience large temperature changes and are often made of anisotropic materials, experimental techniques must be used.

3. Experimental Methods

A common method of experimentally determining a material's expansion coefficient is by using a push-rod dilatometer. With this method, a reference material with a known CTE is cooled with liquid helium to calibrate the measurement system. The sample with unknown thermal expansion properties is then installed into the device and it is cooled in the same manner as the reference material. A typical push-rod dilatometer is shown in Fig. 1.

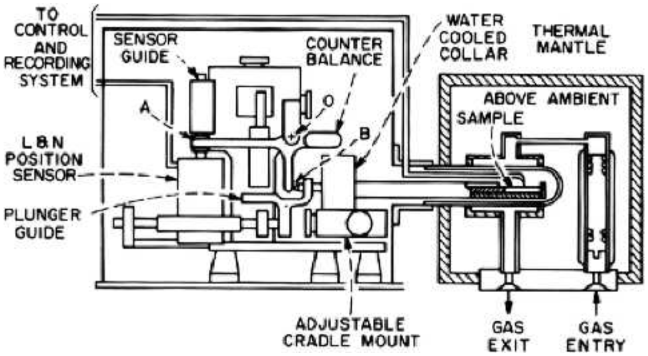

Fig. 1 Push-rod dilatometer for measuring material CTE

The pushrod works on the simple principle that the vitreous silica pushrod will shift vertically, depending upon the expansion or contraction of the specimen. This change in position is interpreted and processed by a computer to obtain the actual thermal expansion of the specimen (Ref 3). The main disadvantage with a push-rod dilatometer is that the results are only as good as the reference material and it is not ideal for very low temperature measurements.

A second, more accurate method of calculating material CTE is to use a Michelson Laser Interferometer (PMIC, Corvallis, OR). This method uses a laser and optical mirrors to measure the length of a test specimen. Figure 2 illustrates a simplified schematic for a Michelson Laser Interferometer.

The advantage of a laser interferometer is that it does not require a reference material to measure the thermal coefficient of expansion. The actual expansion, or change in length, is measured based on the wavelength of the laser (Ref 1). Each shift in a fringe pattern corresponds to a change in the sample length of one half the wavelength of the laser electromagnetic radiation. Using this technique, a resolution of 0.001 ppm/°C is possible (Ref 4).

A final, less common method to measure material expansion is to use a capacitance dilatometer. This measurement technique uses the principle that electrical capacitance is a function of the distance between the two charged plates (Ref 1). A capacitance dilatometer is shown in Fig. 3.

With a specimen in place, the temperature is varied to expand or contract the test sample. As the sample changes length, the amount of capacitance changes accordingly. This technique is capable of measuring resolutions of 10^{-7} millimeters (Ref 5). Currently limited to very small test samples, this method shows promise for more widespread applications after further development.

4. Conclusions

The most common method for measuring the thermal expansion of materials is by using a push-rod dilatometer. While

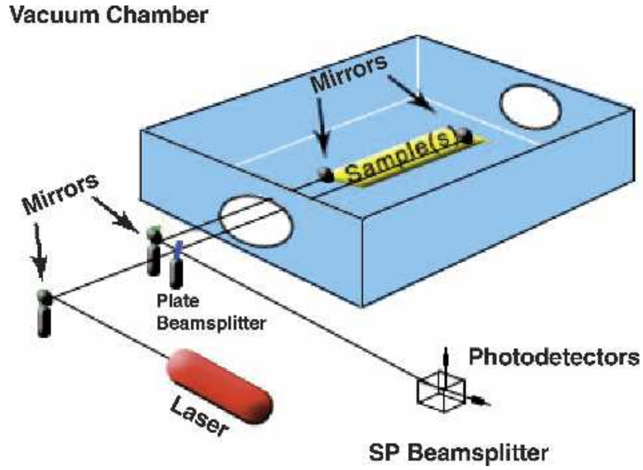

Fig. 2 Michelson laser interferometer for measuring material CTE

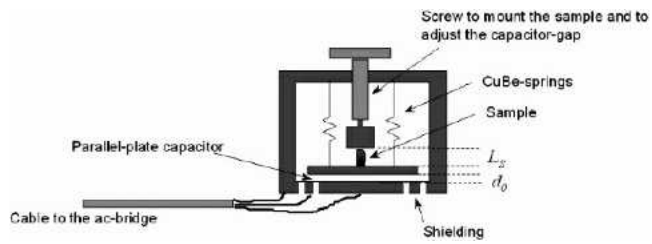

Fig. 3 Capacitance dilatometer for measuring material CTE

this method is adequate for many applications, it is not well suited for the extremely low temperatures experienced in a space environment. For cryogenic temperatures, a laser interferometer yields much better results for CTE calculations. An accuracy of 0.001 ppm/°C is easily attainable with this method. A final technique that can be used to determine a material's expansion coefficient involves a capacitance dilatometer. Although highly precise, this technology is very limited to very small test specimens and is not widely available. It does show promise for future development, however.

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