Laboratory on Thermal Stresses and Strains

Objective

The objective of this laboratory is for you to explore the origin and magnitude of thermally generated stresses and strains.

Preparation

Read on Compass 2G site:

- Chapter 7: Dilatometry and Inferometry
- ASTM E1876-09, Standard Test Method for Dynamic Young's Modulus, Shear Modulus, and Poisson's Ratio by Impulse Excitation of Vibration

Locate values:

- Melting point of borosilicate glass _____________
- Melting point of soda lime glass _______________
- Theoretical coefficient of expansion at various temperature ranges for all materials
    - Borosilicate glass ____________________
    - Soda lime glass _____________________
    - Titanium ___________________________
    - Kovar ____________________________
- Theoretical Young's modulus for all materials
    - Borosilicate glass ____________________
    - Soda lime glass _____________________
    - Titanium ___________________________
    - Kovar ____________________________

Equipment and samples

- Station for thermo-mechanical analysis (Orton Dilatometer)
- Station for measuring elastic constants using the resonant vibrations of a bar
- Samples of Kovar, Ti, borosilicate glass, and soda lime glass
- Computer, data-acquisition board and software, plotting software, microphone, audio analysis software.

Laboratory Safety: Thermal Stresses and Strains

Required Personal Protective Equipment

- Safety glasses with side shields
- Long pants
- Closed toed shoes
- Heat resistant gloves - (will be provided in the lab)

Safety Concerns

- High temperatures and hot materials - potential for burns and fire.
  - Samples will be tested at extremely high temperatures up to 1000°C, which can cause severe burns to skin. High temperature gloves should be worn when touching any part of the furnace or sample assembly during or immediately after a sample run.
  - Heat resistant tools should be used to remove samples from the dilatometer sample holder.
  - Hot samples should never be placed on the bench top or near any combustible materials to reduce the risk of starting a fire. Hot samples should instead be placed in heat resistant trays until they are completely cool.
  - Keep all combustible materials away from the dilatometer.
- Broken glass and sharp objects - potential for cuts
  - Glass samples will be tested in this experiment. Care should be taken not to drop these samples due to the possibility of fracture. Once fractured the samples can pose a risk as a sharp object capable of causing cuts to exposed skin.
  - Glass samples should be inspected for cracks and fractures before placing them in the sample holder to be tested. A cracked sample may become further damaged during testing, potentially sending broken pieces of glass into the workspace.

Waste Considerations

- No waste is generated from this experiment.
- Broken glass samples must be thrown away in a lab glass disposal box, and not the normal garbage.

Experimental procedure:

Introduction

Materials processing frequently involves elevated temperatures. An example is the joining of glass to a metal for forming air-tight seals for a wide variety of applications. At the temperature where the seal is formed, the glass flows and the stresses are small. But when the structure is cooled to room temperature, differences in the thermal expansions of the metal and glass generate thermal stresses at the interface that have to be managed. If this stress is too high, the seal will fracture or delaminate. The strain in the materials is defined by the difference in bulk thermal expansion coefficients. The thermal stresses are a function of both the thermal strains and the elastic constants (moduli) of the materials.

All materials exhibit a change in dimension that is related to temperature. This is easily understood. When we heat a sample the atoms vibrate more, causing them to gradually move apart on average. Therefore we expect that the size of a material increases with increasing temperature, resulting in thermal expansion. This is not always true. For example, liquid water exhibits a negative thermal expansion coefficient between 0 and 4°C. The thermal expansion coefficient, α , defines the relationship between strain, ε, and ΔT, by

$$\epsilon = \alpha \Delta T$$

As you can tell from the discussion of negative α values, the thermal expansion coefficient can change with temperature. This experiment measures the thermal expansion coefficient of a sample by measuring the change in length of a sample as a function of temperature.

Thermal stresses arise whenever a material cannot freely expand or contract upon heating or cooling. The magnitude of the thermal stress is directly related to the elastic modulus in a linear elastic solid. The elastic modulus can be determined from the vibrational frequency of a cylindrical rod based on ASTM Standard E1876-09:

$$E = 1.6067\left(\frac{L^3}{d^4}\right) m f_f^2 \tau$$

$$\tau = 1 + 4.939\frac{d^2}{L^2}$$

where L is the sample length, d is the sample diameter, m is the sample mass, and f_f is the natural transverse frequency. The proper way to arrange a sample to measure this behavior is to support the sample at two positions where nodes in the transverse vibration occur. The rod is then struck at one end with a round ball attached to a handle. The geometry of this case is illustrated at: Impulse excitation technique as well as in the ASTM standard.

The simplest way to determine the vibrational frequency is using a microphone and then analyzing the sound recorded. That is how you will do this experiment.

Part 1: Thermal strains in common engineering materials

- *Measure elongation of Kovar, Ti, borosilicate glass, and soda-lime glass by dilatometer.* This should cover a reasonably large range of temperatures within the capabilities of the furnace. Be cautious with the glasses above 600 ◦C (at least for the soda lime glass) to avoid melting the sample. Take into account how the heating rate affects the result. *Try to determine how the thermal expansion value measured changes with time and report the time dependence of the results.*

Part 2: Elasticity in common engineering materials

- While your furnace heats, *measure the elastic constants of Kovar, Ti, borosilicate glass and soft glass by resonant vibrations.* You will need to investigate the best ways of supporting the sample. *In your report describe the vibrational spectrum you observe and which vibration is the transverse vibrational mode.* Does it matter how you strike the sample?
- *Analyze your results to give the thermal stress of a simple geometry of Kovar-glass and Ti-glass bonds. Which glass pairs best with Kovar and which with Ti?*
- Observe the construction of the experimental apparatus. In your report, explain whether or not you have to worry about the thermal expansion of the parts that hold the sample within the furnace and transmit dilatation to the strain sensor and why this is the case.

Accuracy

- Look up the thermal expansion coefficient and elastic modulus of the samples you are testing and compare those values to your results. What are the uncertainties and possible sources of error? Explain why you would expect the four materials to have different CTE and modulus values.
- Does the measurement of the resonant frequency depend on how the bar is tapped? Does it depend on how the bar is suspended? Do the longitudinal and transverse vibrations give the same result? Why or why not?
- How accurate are the dilatometry measurements? Does changing the temperature ramp-rate change the results? Does this depend on the material? Consider how long it takes for the specimen to come to thermal equilibrium: the time-scale for thermal equilibration by conduction is the radius-squared divided by the thermal diffusivity. For glass, the thermal diffusivity is approximately $D \sim 0.01$ cm^2/s; for Kovar, $D \sim 0.1$ cm^2/s ; for Mo, $D \sim 1$ cm^2/s .

Instrument procedures

Dilatometer - Making an Experimental Run

The following are the general steps to begin an experimental test. The operator is advised to become familiar with the more detailed information in the various manuals before attempting a test run.

Dilatometer

1. Measure test specimen length.

2. Place the test specimen in the sample holder.
3. Position the thermocouple bead.
4. Rotate the LVDT to NULL the LVDT position ("0.100" in RESULT display)
5. Position the furnace over the sample holder.
6. Insert IFB furnace end plug.
7. Run the Orton Dilatometer software, and select "Setup" from the software tabs. Complete the Set-up screen:
    a. Select "Air" from the Tuning Constants.
    b. Type a new File Name.
    c. Enter the sample length.
    d. Select "Experiment” as the type of run.
    e. Select a CAL file. Make sure the selected CAL file was generated using the same test conditions.
    f. Change Start Temperature if desired.
    g. Change Thermal Cycle if desired.
    h. Change Safety Shut-off parameters if desired.
    i. Set Zero Delay Start.
8. Click the [Start Test] button to initiate the test. A series of screens will prompt the user to begin the test.
9. When the test is complete, review the test results.

Measure and Record Resonant frequencies of the materials

- Suspend a 6 inch rod of the material to be tested so that it swings freely
- Set up the microphone in a position that allows for recording of the sound generated after striking the bar. Note that you will be measuring both longitudinal as well as transverse vibrations. You should move the microphone depending on which way the bar is struck.
- Open the software program Audacity and hit record.
- Strike the bar and record the frequency generated.