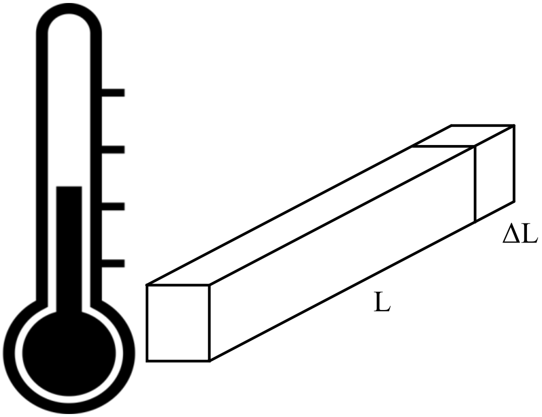
AP001: Thermal Expansion



This application note describes how Razorbill Instruments stress and strain cells respond to temperature changes. It includes details of the thermal expansion of piezoelectric stacks, and the mechanism by which the cells prevent that thermal expansion from affecting the sample. It also describes the remaining effects which are not compensated, the thermal expansion of the rest of the cell. Implications for the sample are described, along with some suggestions of how to mount samples with large thermal expansions. Finally this application note also includes a few notes about other thermal effects such as changes in thermal conductivity of the cell.

Principle of operation

One of the challenges in using piezoelectric elements to strain samples across a range of temperatures is that piezoelectric stacks have an unusual negative thermal expansion: they lengthen along their poled direction when they are cooled. This means that the differential thermal expansion between the piezoelectric stack and typical test samples can quickly exceed the achievable strains of the stacks, that is the zero-strain point moves outside the range of the stacks. Razorbill Instruments stress and strain cells have a symmetric arrangement of piezoelectric stacks that cancels the thermal expansion of the stacks, allowing the sample to remain near zero strain across a wide temperature range. The cells also have piezoelectric stacks much longer than the sample, allowing large sample strains to be achieved. The strain in the sample is the applied displacement ΔL divided by the sample length and users can choose very short samples if necessary.

The way in which this is achieved is illustrated in in Figure 1, which shows a simplified sketch of a CS100 strain cell. There are three piezoelectric stacks in the cell, all three are connected at one end to the “bridge” component, while at the other end one is connected to one end of the sample, and the other two are connected to the other end of the sample. If the inner stack is contracted, and the outer stacks extended, then the device will pull on one end of the sample and push on the other, applying tension. Applying opposite voltages to the piezo stacks causes the opposite effect. Thermal expansions on the other hand expand and contract all three stacks in the same way, so there is no net movement applied to the sample (though the bridge component moves away from the rest of the cell).

The same general arrangement is used in all Razorbill Instruments cells, though not all are a simple as the CS100. The FC100 stress cells, for example, have the three stacks vertically inside the cell. They have a compliant mechanism converting their motion to a horizontal movement on the top surface, and in these cells expanding the inner stack tensions rather than compresses the sample. All cells use some form of compliant mechanism to guide the ends of the sample and keep the strain as uniaxial as possible.

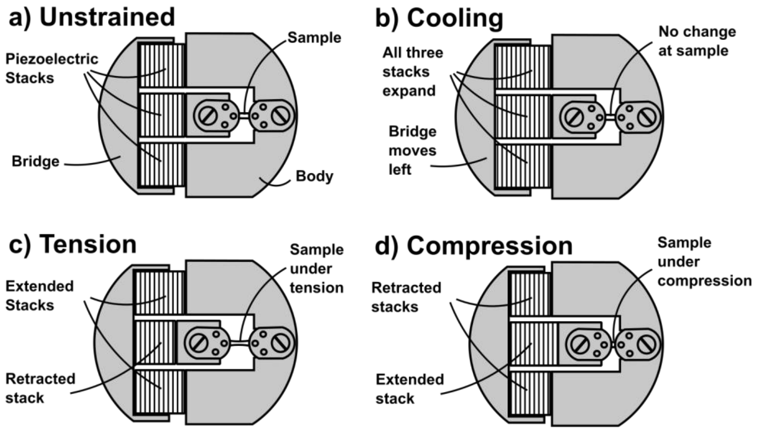


Figure 1. The principle of operation of the cell. Displacements are not to scale.

The compensation effect is not perfect, as piezo stacks have some natural variation in properties due to the manufacturing process. They can also change over time due to age, use, exposure to high temperatures, and recent voltage history. However, the differential thermal expansion between the stacks and typical samples is reduced to much less than the range of movement the cell provides.

What is not compensated

The scheme described above means is designed so that the cell can provide a wide range of strains both sides of zero for samples with a wide range of thermal expansions. This does not however mean that the cell behaves identically at all temperatures. In particular, the piezoelectric stacks used to drive the cell will deliver smaller displacements for the same applied voltage at low temperatures. Achievable strain ranges remain relatively large because the stacks can withstand larger voltages at low temperature. This does mean however that if the temperature changes while the cell is held at a fixed voltage, the strain will change. For this reason, most users do strain sweeps at fixed temperature. If temperature sweeps at fixed strain are required, then some form of closed loop control based on the cell's built-in displacement or force sensors will be needed.

T	$\frac{L_{293}-L_T}{L_{293}}$	$\frac{1}{L_{293}}\frac{dL}{dT}$
K	$\times 10^{-5}$	10^{-6} K^{-1}
0	151	0
20	151	0.08
30	151	0.3
40	150	0.6
50	149	1.2
60	148	2.0
70	145	2.7
80	142	3.4
90	139	4.0
100	134	4.5
120	125	5.3
140	113	6.0
160	101	6.5
180	87.4	6.9
200	73.2	7.3
220	58.3	7.6
240	42.9	7.8
260	27.0	8.0
273	16.5	8.2
280	10.8	8.2
293	0	8.3
300	-5.9	8.4

Table 1: Thermal expansion coefficient and total thermal expansion of titanium from 0 to 300 K, from Thermal Expansion of Technical Solids at Low Temperatures - A Compilation From the Literature by Robert J. Corruccini and John J. Gniewek.

Residual thermal expansion

A mounted sample may still be strained by the differential thermal expansion between it and the material of the chassis, which is pure titanium for all standard Razorbill Instruments cells. If the sample plates are also titanium, the sample will in principle see only the differential thermal expansion between itself and titanium over its own length. The thermal expansion of titanium is provided for reference in Table 1 and Figure 2.

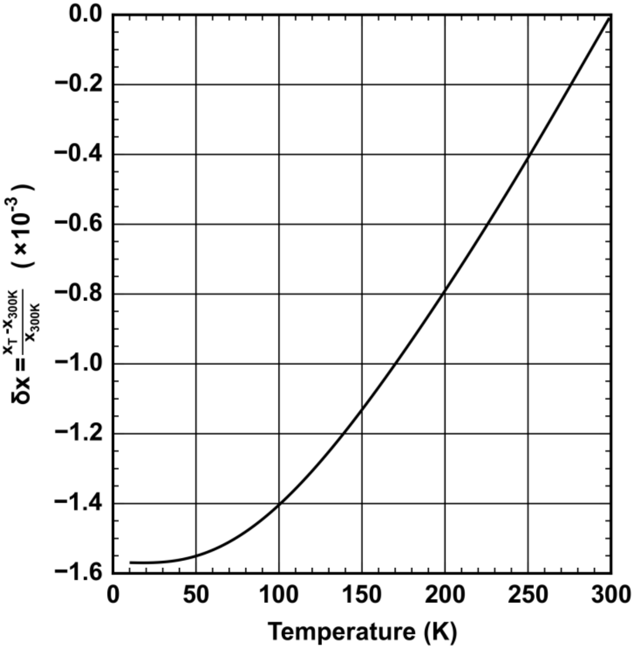


Figure 2. Graph of the linear thermal expansion of titanium. At 4 K the linear dimensions are reduced by 0.15 % compared with their length at 290 K. Compare with Aluminium (0.45 %), copper (0.35 %) and steel (0.2 - 0.35 %).

The difference in thermal expansion coefficient between the sample and titanium will result in the sample being strained when the cell has zero voltage applied. There is no easy way to identify the zero strain point in a strain cell such as the CS100, but a stress cell, such as the FC100, measures force and zero force means zero strain. Separate measurements on an unstrained sample may be useful to identify the zero-strain point.

The relative thermal contraction will also have consequences for the accessible strain range of the sample and cell. Take for example a 2 mm long sample mounted in a CS100 cell with a total thermal expansion to 4 K of 0.25%. This is 0.1% more than the titanium, so with zero voltage applied at 4K the sample will be strained to 0.1 %. The CS100 has a movement range of ± 3 µm, which is 0.15 % of the 2 mm sample length, so the sample strain can be adjusted from 0.05 % compression to 0.25 % tension.

If this means that the desired strain range is no longer achievable, then there are several options for improving it:

- Use a shorter sample. With a 1mm sample the range would be 0.2% compression to 0.4% tension.
- Use a cell with a longer range. With a CS130, the travel is ± 10 µm, which would allow strains from 0.35 % compression to 0.55 % tension.
- “Freezing in” some strain. Note that the position achieved by applying 100V then cooling to 4K will be different to the one achieved by cooling and then applying a voltage. It is often possible to take advantage of the longer range at room temperature to set the strain to the value of interest, then when cold the available travel range will be centred near that point instead of near zero.
- Pre-stress the sample. If the sample is mounted with a small voltage applied to the stacks, then the range can be shifted to be centred on zero strain again. If using this approach, either limit the applied voltage or take other precautions to prevent a shock to the user. Bear in mind that tools like tweezers and scalpels are conductive and could reach parts of the cell which would normally be inaccessible.
- If the sample plates are, e.g., made from a copper-based alloy, then they will contract more than the apparatus during cooling, placing the sample under tension. Similarly, molybdenum or tungsten plates will place the sample under compression.

Heating and cooling

The previous sections all assume that the cell is in thermal equilibrium. If the cell is heated or cooled too quickly, then it some parts of it may be hotter than others. This is particularly an issue with the piezo stacks, as they have a very large thermal expansion mismatch with the rest of the cell. If the central stack is warmer than the outer pair, for example, it will apply tension to the sample.

How quickly is “too quickly” depends on the cryostat, and how the cell is thermally connected to the cryostat. But 10 K/minute should be considered an absolute upper limit. In most cases, it will be necessary to see how long it takes for measurements to settle after a temperature change, and then pick a temperature rate accordingly.

Other thermal effects

As with all metals, the thermal conductivity of titanium reduces as it cools, and titanium is generally less conductive than most pure metals. The titanium grade used in the cells also goes superconducting about 300 – 400 mK, which drastically reduces the thermal conductivity. In measurements where power is dissipated in the sample and/or precise temperature control is necessary, it may be useful to connect the sample to a thermometer and the cold finger with silver foil. Razorbill Instruments can provide advice on how to do this.

Temperature will also affect the reading of the capacitance sensor, but this varies between different types of cell. Refer to the datasheet for your cell and AP006 for more information.