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TECHNICALTIDBITS

MATERION PERFORMANCE ALLOYS

MEASURING THERMAL CONDUCTIVITY - PART 1 - HEAT FLOW METERS

Watt's up! – How thermal conductivity uses specially designed conductivity meters.

- **Thermal Conductivity**
- **Steady State Heat Transfer**
- **Transient Heat Transfer**
- **Heat Flow**
- **Heat Flux**
- **Heat Flow Meter**
- **Thermal Conductivity Meter**

Thermal conductivity is a measure of the rate of heat flow through a material. It is not easy to quantify, since it can't be directly measured. However, there are a number of other more or less easily measured parameters that depend on the conductivity. These parameters are measured and the conductivity is calculated from them. Note, however, that different methods do not necessarily produce the same results.

Heat transfer is a complicated subject. Most engineers have taken multiple courses back in their university days to cover the subject. To quickly summarize, thermal energy moves from areas of high concentration (hot areas) to areas of low concentration (cold areas), in spontaneous search for thermal equilibrium. **Steady state heat transfer** occurs when thermal equilibrium is met and maintained. **Transient heat transfer** is what happens while the system is on its way to thermal equilibrium. In both cases, thermal energy moves from hot to cold by conduction (direct contact between different materials), convection (through the movement of adjacent fluids), and/or radiation.

Real-world heat transfer problems have complicated geometries, with heat moving in all directions by all 3 methods, and are rarely in a steady state condition. The general equation for pure thermal conduction in a body without internal heat generation is:

$$\rho \cdot c_\rho \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\kappa \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\kappa \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\kappa \frac{\partial T}{\partial z}\right)$$

However, we are talking about thermal conductivity as a material property, and not about general heat transfer, so we will ignore all that and look at an ideal case. Figure 1 shows 1-dimensional heat conduction through a simple geometry under steady state conditions, with no heat transfer by convection or radiation. (One dimensional implies that the heat is only moving in one direction, with no perpendicular component. The temperature changes only along the length, and the entire cross section at any given point along the length is at a uniform temperature.)

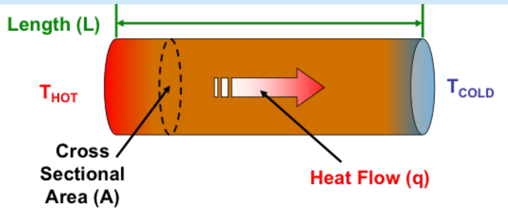

Figure 1. Simple Representation of 1-Dimensional Heat Conduction through a Cylindrical Specimen. At steady state, if the ends are maintained at their respective temperatures, there is constant thermal gradient through the specimen, and a constant flow of heat from the hot side to the cold side.

Under such 1-dimenional steady state conditions, the following equation describes heat conduction:

$$q = -\kappa \cdot A \frac{dT}{dx} = \kappa \cdot A \frac{({}^{T}\text{Hot} - {}^{T}\text{Cold})}{L}$$

where A is the cross sectional area of the specimen, *L* is the distance between the hot face and the cold face, κ is the thermal conductivity, and q is the **heat flow**. So, with a given cross sectional area, conducting path length, and a temperature difference from end to end, the thermal conductivity determines the rate of heat flow.

Rearranging the equation, you get

$$\frac{q}{A} = -\kappa \cdot \frac{dT}{dx} = \kappa \cdot \frac{({}^{T}\text{Hot} - {}^{T}\text{Cold})}{L}$$

This puts the equation in terms of **heat flux** (q/A), which is the amount of thermal energy passing through the area within a given time.

The next issue of Technical Tidbits will discuss methods to determine thermal conductivity by measuring the total heat transfer.

THERMAL CONDUCTIVITY METERS (CONTINUED)

To improve heat flow out of a hot zone in a device, you can do one of four things:

1. Increase the cross sectional area (A)
2. Decrease the distance between the heat source and heat sink (L)
3. Reduce the temperature of the cold side $({}^{T}\text{Cold})$
4. Increase the thermal conductivity of the heat transferring material (κ)

Since the available spaces on most devices are limited, and cooling is usually limited to ambient temperature, options 2 and 4 are the only reasonable choices for consumer environments. Number 2 is why heat spreaders are so thin, and why heat sinks are mounted directly on top of processors whenever possible.

Number 4 is why thermal conductivity is becoming increasingly important in consumer electronics devices. Remember that heat must usually pass through multiple materials on its way to dissipation from the processors. The material with the lowest thermal conductivity usually dominates the overall thermal conductivity of the path, unless it is extremely thin. Therfore, it is important to know the thermal conductivity of all the materials in the path.

To measure thermal conductivity with a **heat flow meter** (also known as a **thermal conductivity meter**) you will need to replicate the 1-dimensional steady state condition as closely as possible. This means that the specimen should be insulated around the sides, so no significant heat is lost through the sides by conduction, convection, or radiation. The temperature on the hot side and the cold side must be carefully maintained. Thermocouples measure the temperature difference, $A({}^{T}\text{Hot} - {}^{T}\text{Cold})$ and sensors (thermal transducers) on either side of the sample measure the heat flow (q). If you input the sample length (L) and cross sectional area (A), then the thermal conductivity can then be easily calculated and reported by the meter.

$$\kappa = \frac{q \cdot L}{A({}^{T}\text{Hot} - {}^{T}\text{Cold})}$$

Alternatively, you can measure q by measuring the power consumed to electrically heat the hot side, since that will be equal to the thermal energy produced. Of course, good insulation is required, since the latter method assumes that the overwhelming majority of the heat generated passes through the sample to the cold side and an insignificant amount is lost through other paths.

To achieve steady state conditions in a low thermal conductivity (high thermal resistivity) material within a reasonable time frame, the ratio of the cross sectional area to the length needs to be high. Therefore, disk-shaped samples are used. Higher conductivity metals achieve steady state quickly no matter what the sample size and shape are. However, a larger distance between the hot and cold faces is required for adequate resolution of the heat flow and temperature gradient. Therefore, relatively long cylindrical or rectangular prisms are used for the test specimen. The next issue will discuss some specific measurement methods that use these principles.

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ASTM E-1225-13 Standard Test Method for Thermal Conductivity of Solids Using the Guarded-Comparative-Longitudinal Heat Flow Technique ©2013 ASTM International

ASTM E-1952-11 Standard Test Method for Thermal Conductivity and Thermal Diffusivity by Modulated Temperature Differential Scanning Calorimetry ©2011 ASTM International

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