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MATERION

TECHNICALTIDBITS

MATERION PERFORMANCE ALLOYS

CURRENT EVENTS: ELECTRICAL AND THERMAL CONDUCTIVITY

Like two peas in a metallic pod. – How electrical and thermal conductivity are related in copper alloys.

- Electrical Conductivity
- Thermal Conductivity
- Free Electrons
- Wiedemann-Franz Law
- Phonon Waves
- Phonon

The next issue of Technical Tidbits will discuss defining the maximum operating temperature of a material.

By definition, **electrical conductivity** is a measure of how well electrical current (charge in motion) can pass through a material under the influence of an applied voltage/electric field. **Thermal conductivity** measures how well heat (thermal energy in motion) can pass through a material under a temperature differential.

In metals, both electric current (flow of charge) and heat transfer (flow of thermal energy) are primarily carried by electrons. The conductivities of metals therefore depend on how many free electrons are available to flow through the metal. (Free electrons are typically unpaired valence electrons.) In conductive metals, they are only loosely associated with the atomic nucleus, and are free to move around in the metal. Metals atoms can be thought of as islands in a sea of shared free electrons. The electrical and thermal conductivities of a metal therefore depend on both the number of free electrons, as well as how tightly coupled they are to the nucleus.

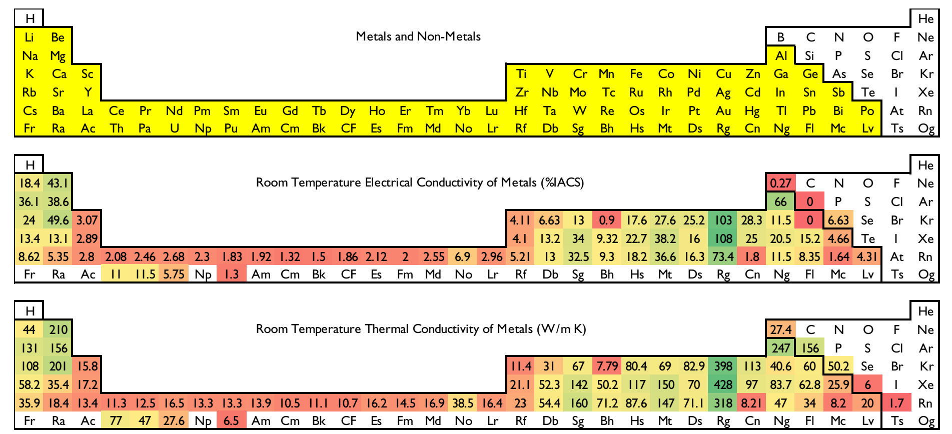

Figure 1. Electrical and Thermal Conductivities of Pure Metals.
The displayed conductivity values are color-coded according to their relative magnitude. Note that electrical and thermal conductivities have the same relative magnitude, except for the metalloid elements near the boundary between the metals and non-metals. In the non-metals, electrons have little mobility, and heat is transferred by other mechanisms. These elements have widely varying thermal conductivities depending on form and structure, so there is no single value to put in the charts above. [Sources: ASM Handbook Vol. 2 and Wikipedia]

As shown in Figure 1, the highest conductivities are found in the transition metals. Electron mobility, crystalline structure and physical state (solid or liquid, single phase or multiple phases) all play a role in determining what the conductivities are. In the metals, electron mobility dominates thermal and electrical conductivity. If the electrical conductivity is high, then the thermal conductivity will be high as well. In non-metals, heat is conducted by other methods, and electrical conductivity is virtually nonexistent.

In the non-metals, crystalline structure becomes more important in determining thermal conductivity. For example, compounds of pure carbon have varying degrees of conductivity, which can differ by an order of magnitude depending on the atomic arrangement. Note also that while diamond is a virtually perfect electrical insulator, its thermal conductivity is greater than that of any metal. Further note that carbon nanotubes have decent electrical conductivity, indicating greater electron mobility in that crystalline form than in graphite or diamond form, despite having the same electron configuration.

Form of Carbon	Electrical Conductivity	Thermal Conductivity
Graphite	0.22 % IACS	119 - 165 W/m K
Diamond	~0% IACS	900 - 2300 W/m K
Carbon Nanotubes	1-20 % IACS	> 3000 W/m K

CURRENT EVENTS: **ELECTRICAL AND THERMAL CONDUCTIVITY** (CONTINUED)

The electrical and thermal conductivities of metals are related by what is known as the Wiedemann-Franz Law, which can be stated as $\lambda=(L\cdot T)/\rho$, where λ is the thermal conductivity (in Watts/m K), T is the absolute temperature (in K), L is the Lorenz Constant (2.45×10^{-8} Volt^2/K^2), and ρ is the electrical resistivity (in $\Omega\cdot$m). (Note that electrical resistivity is the inverse of the conductivity and yes, the units do work out properly).

You can easily see the Wiedemann-Franz relationship in the color coding of the periodic tables in Figure 1. So, if it holds for pure metals, does it hold for alloys as well? The answer is yes, even though there are other elements present in the copper alloy matrix. Since the alloying elements disrupt the mobility of the electrons, both electrical and thermal conductivities are reduced by the same factor. You can see this clearly in Figure 2.

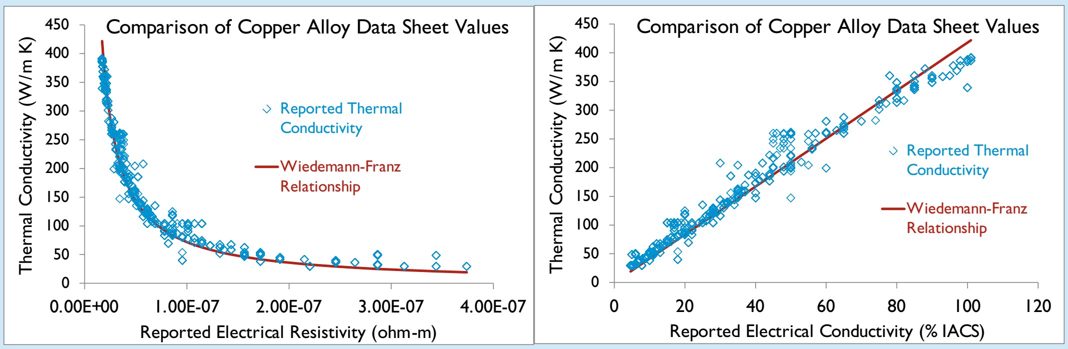

Figure 2. Electrical and Thermal Conductivity as Reported on Various Data Sheets.
There is only minor variation from the Wiedemann-Franz relationship. The left chart shows the relationship between the variables as presented in the equation. The right chart shows that in copper alloys, there is a linear relationship between thermal and electrical conductivity.

So, if electrons are not the primary conductor of heat in non-metals, then what is? Temperature is a measure of the average kinetic energy of the vibrations of the individual atoms in the crystalline lattice.

In non-metals, the thermal energy moves through the material as a wave of vibration. These waves are elastic waves, and behave similarly to sound waves moving through a material. Such waves are called **phonon waves**. (In fact, a sound wave is essentially a low frequency phonon wave). These waves, like most everything else in physics, are quantized, which means that they only exist in discrete multiples of the base state. In this case, a quantized vibrational wave is called a **phonon**. Thermal energy is transferred back and forth between the electrons and the moving phonons.

Phonon waves can pass more easily through some atomic arrangements than through others. This is why thermal conductivity of non-metals will vary greatly depending on the crystalline structure.

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