MATERION

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**TECHNICAL**TIDBITS

MATERION PERFORMANCE ALLOYS

**Too hot to handle, too cold to hold! –** Two more thermal properties that influence how efficiently a material can transfer heat.

- **Thermal Diffusivity**
- **Thermal Conductivity**
- **Heat Capacity**
- **Effusivity / Thermal Permeability**

*The next issue of Technical Tidbits will discuss thermal expansion and contraction.*

# THERMAL DIFFUSIVITY **AND EFFUSIVITY**

Whereas thermal conductivity describes how quickly heat flows through a material from the hot side to the cold side under steady state conditions, **thermal diffusivity ($d_t$)** describes how well a material can spread heat, taking into account both how quickly the heat can be conducted through (**thermal conductivity** $\kappa$) and how quickly its own temperature can change when the material is heated (**heat capacity** $c_p \cdot \rho$). Since it takes into account how much energy is absorbed in heating the material to the temperature gradient, it tells you more about what is going on in transient heat transfer than conductivity alone. Specifically, thermal diffusivity describes how quickly a material under transient heat conduction converges to steady state heat transfer. It is calculated as: $d_t = \frac{\kappa}{c_p \cdot \rho}$ and its units work out to area per unit time ($m^2/s$ in SI and $in^2/s$ or $ft^2/s$ in imperial units).

The general equation for conductive heat transfer is as follows (assuming uniform thermal conductivity throughout the sample and no internal heat generation:

$$\rho \cdot c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\kappa \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\kappa \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\kappa \frac{\partial T}{\partial z}\right) = \kappa\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right)$$

Rearranging,

$$\frac{\partial T}{\partial t} = \frac{\kappa}{\rho \cdot c_p}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) = \frac{\kappa}{\rho \cdot c_p} \cdot \nabla^2 T = d_t \cdot \nabla^2 T$$

That last equation can be printed as simply: $\frac{\partial T}{\partial t} = d_t \cdot \nabla^2 T$. This means that the change in temperature over time is equal to the thermal gradient through the material times the diffusivity. Therefore, it is the thermal diffusivity that truly governs the speed of heat conduction. Thermal conductivity is a strong contributor to thermal diffusivity, but is not the entire story. For good diffusivity, you would like high conductivity and low heat capacity.

| Alloy Name | Alloy Type | Density | Specific Heat | Heat Capacity | Thermal Conductivity | Thermal Diffusivity | Thermal Effusivity |
|---|---|---|---|---|---|---|---|
| | | $kg/m^3$ | J/kg K | $J/m^3 K$ | W/m K | $m^2/s$ | $J/m^2 K/s$ |
| AISI 420 | Tool Steel | 7810 | 460 | 3592600 | 20 | 5.6E-6 | 8,477 |
| AISI P20 | Mold Steel | 7850 | 460 | 3611000 | 24 | 6.6E-6 | 9,309 |
| AISI H13 | Tool Steel | 7800 | 460 | 3588000 | 26 | 7.2E-6 | 9,659 |
| MoldMAX XL | CuNiSn | 8910 | 389 | 3465990 | 70 | 20.2E-6 | 15,576 |
| MoldMAX HH | CuBe | 8360 | 406 | 3394160 | 130 | 38.3E-6 | 21,006 |
| MoldMAX LH | CuBe | 8360 | 406 | 3394160 | 155 | 45.7E-6 | 22,937 |
| QC-10 | Aluminum | 2850 | 879 | 2505150 | 155 | 61.9E-6 | 19,705 |
| MoldMAX V | CuNiSiCr | 8690 | 410 | 3562900 | 160 | 44.9E-6 | 23,876 |
| C18000 | CuNiSiCr | 8750 | 385 | 3368750 | 235 | 69.8E-6 | 28,136 |
| Protherm | CuNiBe | 8830 | 381 | 3364230 | 250 | 74.3E-6 | 29,001 |
| C11000 | Cu | 8890 | 385 | 3422650 | 388 | 113.4E-6 | 36,442 |

**Figure 1. Comparison of the thermal properties governing heat conduction for several materials used for plastic molding, ranked from lowest to highest diffusivity.** For optimal cooling of molded plastic parts, the mold tool material must efficiently conduct heat away from the plastic resin into water circulating through the cooling channels in the mold. High diffusivity materials will allow for the lowest cycle time. However, the heat transfer characteristics must be balanced against hardness (for wear resistance) and toughness.

# THERMAL DIFFUSIVITY **AND EFFUSIVITY** (CONTINUED)

**Thermal effusivity** (e), also known as **thermal permeability,** measures how well a material can exchange heat with whatever substance it comes into contact with. It is defined as the square root of the product of the thermal conductivity and heat capacity: $e = \sqrt{(\kappa \cdot \rho \cdot c_p)}$. The units work out to a rather ugly-looking $\frac{J}{m^2 \cdot K}\sqrt{\frac{1}{s}}$ in SI and $\frac{BTU}{ft^2 \cdot {}^\circ F}\sqrt{\frac{1}{hr}}$ in the US system.

Effusivity seems like a contrived material property, but it does have real meaning. If two previously separated materials of different effusivities ($e_1$ and $e_2$) and different temperatures ($T_1$ and $T_2$) suddenly come into contact, then the surface of each material at the contact interface between the two will quickly reach a temperature of: $T_{interface} = \frac{T_1 e_1 + T_2 e_2}{e_1 + e_2}$ .

Thermal effusivity thus influences thermal stresses and strains during transient heat conduction, and plays a key role in thermal fatigue and thermal shock. (These topics will be covered in a future issue of Technical Tidbits).

Figure 1 shows and illustrative example of two materials being brought into contact. The temperature of the interface will rapidly approach the value listed below. The interface temperature will be closest to that of the higher effusivity material. This means that materials with high thermal permeability will be able to rapidly heat or cool materials with lower thermal permeability. This is why liquid plastic resin (high temperature, low effusivitiy) solidifies almost instantly when it comes into contact with a metal mold (low temperature, high effusivity). While the resin in contact with the mold wall is instantly frozen, away from the wall it continues to flow freely until the mold is filled. Then the majority of the mold cycle time is taken up by conventional heat transfer, conduction through the resin, conduction through the mold, and convection into the water in the mold's cooling channels.

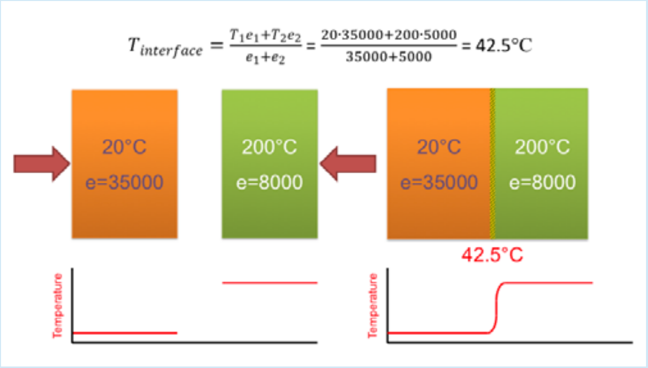

**Figure 1. How the thermal effusivities determines the interface temperature of two bodies suddenly brought into contact with each other.** Note that the temperature is closest to that of the body with the higher thermal effusivity.

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**References:**

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Frank Kreith & Mark S. Bohn Principles of Heat Transfer ©1993 West Publishing Company

Agustin Salazar "On Thermal Diffusivity" European Journal of Physics Vol 24 2003

"Technical Tidbits" Issues 23, 104 & 106

ASTM E-1461-13 Standard Test Method for Thermal Diffusivity by the Flash Method ©2013 ASTM International

ASTM E-2585-09 Standard Practice for Thermal Diffusivity by the Flash Method ©2009 ASTM International

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**TECHNICAL**TIDBITS

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