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TECHNICALTIDBITS

MATERION PERFORMANCE ALLOYS

Heat check yourself and you'll wreck yourself! – A brief discussion on a number of other thermal properties.

- Thermal Strain
- Thermal Stress
- Thermal Fatigue / Heat Checking
- Thermal Fatigue Resistance Parameter
- Thermal Shock
- Thermal Shock Resistance Parameter

The next issue of Technical Tidbits will discuss thermal emissivity.

THERMAL FATIGUE AND THERMAL SHOCK

Due to thermal expansion, objects will expand when heated and contract when cooled. If such an object were completely unconstrained, the change in dimensions can be computed from the thermal expansion coefficient, as discussed last month. However, solid objects in systems are rarely completely free to expand and contract without limit. If some kind of constraint prevents the material from expanding or contracting by the required amount, then the material experiences **thermal strain** and **thermal stress**.

Heat checking, or **thermal fatigue**, can happen when a surface is repeatedly heated and cooled, commonly found in molds used for die casting or injection molding of liquid metal. When the metal surface comes into contact with liquid that is several hundred degrees hotter, the surface will quickly heat up and expand. Meanwhile, the core of the metal is still at the initial temperature. If the material has poor diffusivity, there will be a large gradient in temperature between the surface and the core, and thus a large gradient in thermal strain and stress as well.

The surface will want to expand greatly, but it will be constrained by the core material below, which effectively puts compressive stress on the surface. At a high enough temperature, the stress will exceed the strength of the material, and it will stay in that state. When the thermal load is removed and the metal is allowed to cool, the surface will be unable to shrink as much as the core, since it has been permanently deformed. This places the surface into a state of tensile stress. Over many such cycles of alternating compressive and tensile stress, fatigue cracks can develop on the surface. Usually, the surface takes on a crazed appearance like old pottery (Figure 1).

Figure 1. Crazing on Ceramic Surface. The inside of this coffee mug has a crazed appearance due to thermal cycling in an automatic dishwasher. This is why it is important to teach your children what the phrase "Hand wash only" means.

Metallurgical phase changes can make heat checking worse, if the metal transforms from one solid phase to another upon heating, and vice versa on cooling. This is particularly true when two phases have different crystalline structures or densities.

If heat checking is a potential issue in your application, you should consider using a material with a high **thermal fatigue resistance parameter** (Q). It is calculated as: $Q=(\kappa \cdot \sigma_y)/(E \cdot \alpha)\ (1-\nu)$, and has the units of W/m or BTU/ft hr. A high thermal conductivity (κ) minimizes the thermal gradient within the material, decreasing the differential thermal expansion. A high yield strength (σ_y) minimizes the amount of plastic deformation that occurs on heating and cooling, reducing the tendency to initiate a crack. A high elastic modulus (E) increases the stress at a given amount of thermal strain, so the lower the modulus, the better. A high thermal expansion coefficient (κ) also increases the thermal strain. The ($1-\nu$) term accounts for a biaxial stress state. This assumes that an entire surface is heated, so the material expands in two directions instead of one. Most metals have a Poisson's ratio (ν) of around 0.3, so when comparing different materials, this term can usually be safely ignored. Note also that the equation for Q has the term (σ_y/E) in it, which is the elastic resilience of the material. Therefore, thermal fatigue is yet another failure mode that you can protect against by using a highly resilient material.

THERMAL FATIGUE AND **THERMAL SHOCK** (CONTINUED)

Alternatively, when you know what the thermal cycle will be, you can use the fatigue strength at the mean temperature in place of the yield strength for the thermal fatigue resistance parameter. This would require you to also have the appropriate elevated temperature fatigue data for the material of interest. However, when you are simply making a first pass through multiple materials for a thermally cycled application (such as a water cooled plunger for die casting of aluminum alloys), the yield strength provides a perfectly reasonable comparison.

Thermal shock is similar to thermal fatigue, except that the failure occurs during a single, rapidly applied thermal load. (While thermal fatigue is a cumulative process over many cycles, thermal shock failures are immediate.) This is usually more of a concern in ceramics or other brittle materials that lack ductility, where the initiation of a crack would likely lead to catastrophic failure. Thermal shock failures are familiar to anyone who has ever accidentally set a piece of cold ceramic dinnerware onto a hot stovetop, or mistaken plain glass cookware for tempered borosilicate glass.

The Thermal shock resistance parameter (R_T) $R_T=(\kappa\cdot\sigma\_T)/(E\cdot\alpha)\ (1-\nu)$ has the same units as the thermal fatigue resistance (*W/m* or *BTU/ft hr*), and the formula is virtually identical, with tensile strength replacing yield strength. (Since tensile strength is higher than the yield strength, if a material has a high thermal fatigue resistance parameter, it will also have a high thermal shock resistance parameter.) R_T describes how well a material can theoretically resist cracking (*initiating a new crack*), which is why the tensile strength is used in the formula instead of the yield strength.

In defining thermal shock resistance, some engineers prefer to replace the tensile strength with the plane strain fracture toughness K1C, as follows: $R_T=(\kappa\cdot K\_1C)/(E\cdot\alpha)\ (1-\nu)$. In this case, the units become *W/√m or BTU/hr√ft*. The second equation would be appropriate if there are pre-existing cracks in the material, so the formula then describes theoretical resistance to catastrophic *propagation of an existing crack*. If you have ever had a small crack in your windshield grow to a large crack over a period of a day or two, due to swings in the outdoor air temperature, then you are familiar with this particular failure mode

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