How alloy selection figures in design of radiant tubes

by JAMES SKARDA

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While process requirements may make operating temperatures inflexible, design of the heat source is one area that can contribute to thermal efficiency.

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Fuel efficiency is a function of the total system: furnace, heat source, and the work being processed. Since process requirements typically determine temperature levels, the heat source is the one controllable factor toward improved energy conservation.

Because it is both protective of the environment and more economical than an electrical heating element, the radiant tube has become the preferred heat source in most heat treating environments. In designing a tube with maximum thermal efficiency, proper alloy selection is a prime consideration. Understanding the heat transfer process and mechanism simplifies selection.

Thermal efficiency is directly proportional to the mass to be heated. The amount of energy (Q) required to raise the temperature of a tube can be calculated by multiplying mass or weight (M) times the specific heat of the metal (S) times the resultant change in absolute temperature. Stated mathematically: $Q = MS (\Delta T)$.

Since variation in specific heat (S) is insignificant, the real variant occurs in metal thickness or mass. Therefore, the thicker the tube wall, the more energy is required to raise the temperature to the desired level.

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The rate at which heat is transferred is another indication of efficiency. Heat flow decreases as thickness increases. Fourier's Law states: Heat flow is proportional to surface area and temperature difference, and inversely proportional to wall thickness. If Q = heat energy, t = unit time, K = thermal conductivity coefficient, L = wall thickness, A = surface area perpendicular to the heat flow axis, and $(T_2\text{-}T_1)$ = the temperature difference between the inside and outside surface, this law is expressed mathematically:

$$\frac{Q}{t} = \frac{KA\,(T_2-T_1)}{L}$$

Thin-walled radiant tubes are obvious energy savers. They also provide other benefits. Reducing mass reduces thermal stress and this in turn increases component life, offering additional economies.

Since gas- or fuel-fired radiant tubes incorporate all three basic methods of heat transfer, a review of these heat flow mechanisms is in order.

Conduction is the transfer of heat through the interaction of atoms. This is illustrated by putting a spoon in a cup of boiling water. Because heat flows up the handle through conduction, the handle grows hot, even though it is not immersed in the water.

Radiation is the transfer of heat through space by means of electromagnetic waves. Radiation is directional, i.e., it follows the line of sight. An example of this is the warmth experienced when standing in front of an open fire.

Convection is heat transfer by mixing. An example of this can be seen when water is heated in a pan. As portions of the water are heated, localized changes in density create eddy-like currents, mixing hot and cold portions. Although the water is not being stirred, visually, it appears to churn.

Transfer of heat from the flame inside the tube to the tube surface is accomplished via radiation and convection. Radiation is a direct function of the fourth power of the absolute temperature of the radiating body (the flame) and the path it must travel to the tube wall. Convection is a function of temperature and residence time.

Transfer of the heat through the tube wall is by conduction. Heat absorbed on the inside surface is transferred to the exterior surface of the tube, then to the furnace interior and to the work in progress.

Alloy selection should be predicated on achieving the thinnest-walled tube possible, with only enough thickness to support the tube and contain the internal pressure generated by the combustion process.

Selection is also determined by the alloy's properties and composition. There are five major areas of consideration: strength at temperature; environmental resistance; chemical and metallurgical stability; shock/fatigue resistance, and fabricability. Since there is rarely an exact match between application and alloy, judicious selection often may require a compromise:

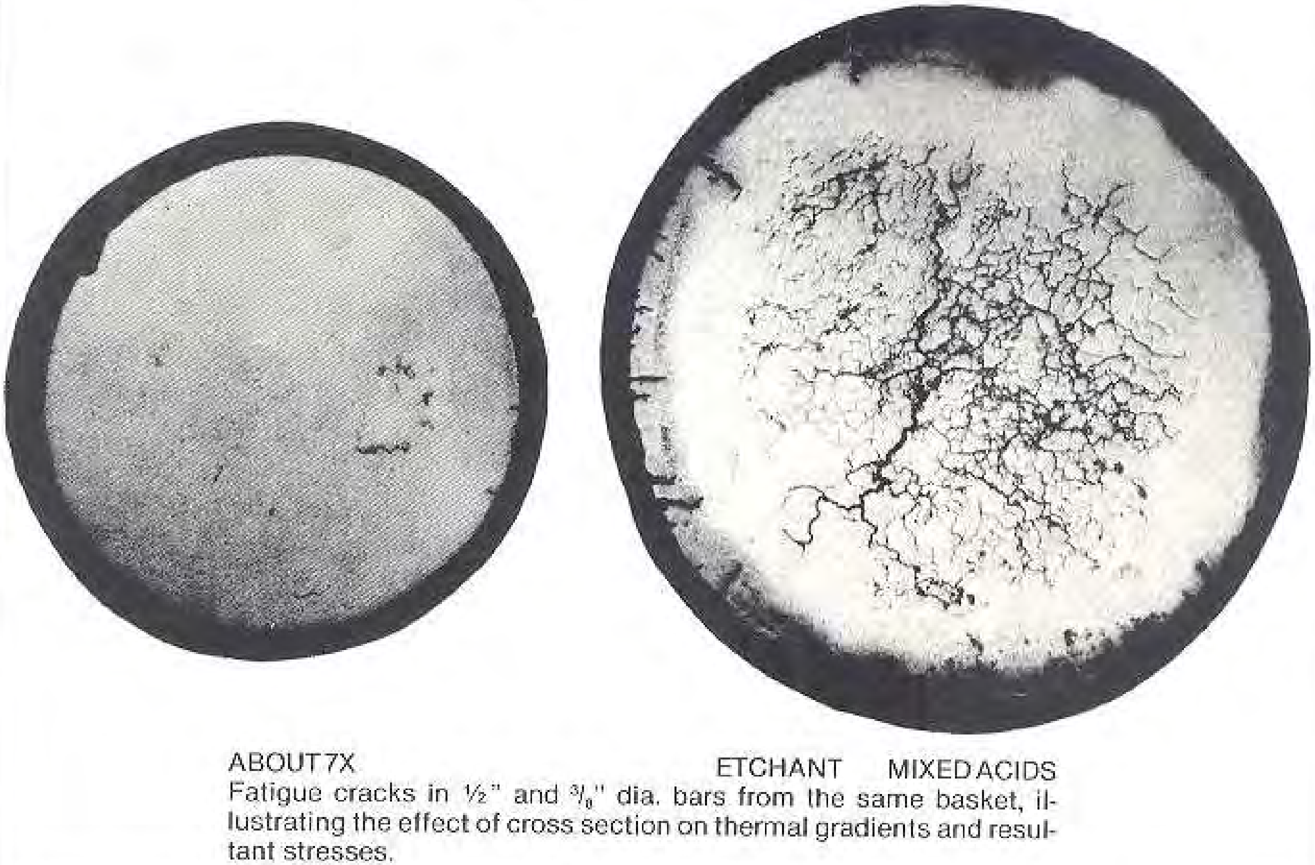
Strength at temperature: Variations in chemical composition or alloy grain size influence strength at temperature. While base strength is largely controlled by chemistry, grain size plays an important role in fine-tuning the various properties involved, and in some cases influences general atmosphere resistance as well.

Before comparing alloys, the designer must consider the type of load involved in order to properly determine which properties to compare. At room temperature the usual criteria is tensile strength. But in furnace environments, most designs are based on creep. Sometimes it may involve evaluation of minimum or secondary creep rate data. In other cases where high ductility alloys or very long service life is a factor, total creep may be the preferred design criteria. Unfortunately, there are no basic rules in this area. Service experience is usually the best guide in choosing proper design criteria. Once the choice is made, a review of technical data sheets on the various alloys will usually provide the necessary background information.

Environmental resistance: Alloy selection for furnace environments involves consideration of the alloy's ability to withstand oxidation, carburization and/or sulfidation, either individually or in combination. While laboratory data provides a good basis for comparison in the area of creep and mechanical properties, considerably less data exists with respect to environmental resistance. This is because the protective film built into alloy systems is constantly changing in response to the environment, and is more difficult to measure.

Data must be very carefully evaluated. Generally, data presented is valid only for the specific conditions and time frame involved in the test period. For convenience, testing time is frequently limited, sometimes 100 hours or less. However, some dramatic shifts in behavior may occur as the test period is extended. Basing alloy selection on short term tests for equipment that is designed to function for years is risky extrapolation. Long term rather than short term testing, and in-service evaluation rather than long term testing, provide a more consistent basis for alloy improvement programs.

Figure 1 - Fatigue cracking



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Fatigue cracks in ½" and ⅜" dia. bars from the same basket, illustrating the effect of cross section on thermal gradients and resultant stresses.

Alloy selection

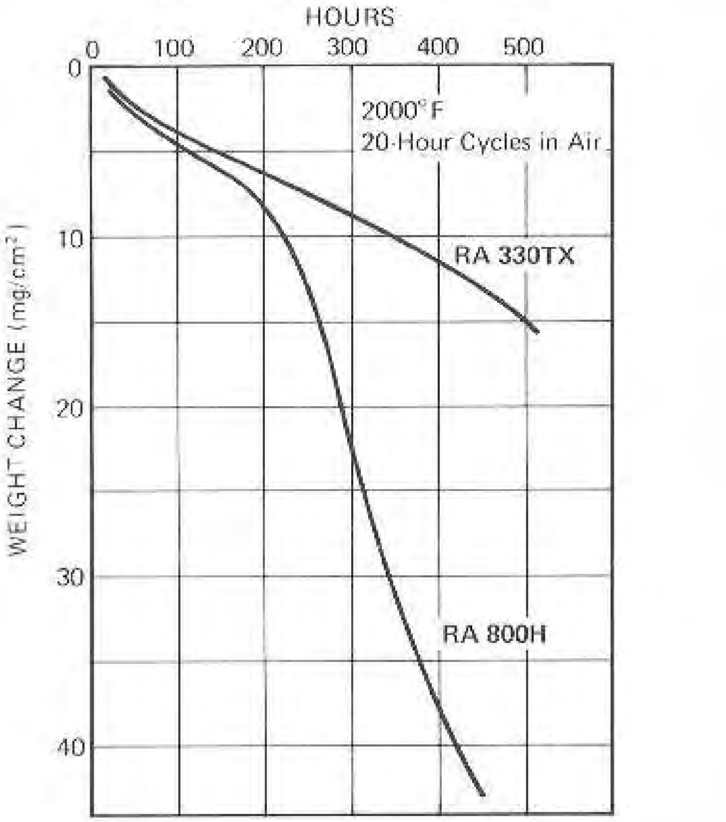
This can best be seen in the chart in Figure 2, which compares oxidation effects on RA 330 TX and RA 800 H. Alloy performance at the end of 100 hours reflects almost identical weight changes. Yet comparison at 500 hours yields quite different results. Similar results will occur for almost any property measured, whether it be oxidation, carburization or sulfidation. It is therefore critical that short term data be used only as a guide and not as an absolute.

Chemical and metallurgical stability: The composition of an alloy is constantly changing. Certain alloys undergo changes in structure and properties purely as a function of temperature changes. Others absorb elements from the environment which in turn change the composition of the original alloy. As a result of these two factors, alloys undergo a continuous adjustment in properties. Furnace alloys must be able to resist these changes if they are to have useful engineering life. Awareness that these changes may occur can prevent costly errors in material selection.

Shock- and fatigue-resistance: Heat resisting alloys are subject to both mechanical and thermal abuse. In areas where mechanical abuse is of primary concern, the best barometer is ductility. Designers should therefore look for materials that are ductile and in general have fine grain size. Awareness of the tendency to embrittle in service must also be considered, because alloys that possess poor chemical or metallurgical stability and embrittle as a result, will fail even though they were originally quite ductile.

Process conditions impose significant thermal abuse on components. Therefore, it is very important to design out notches, abrupt section changes, and restrict thicknesses to the absolute minimum necessary to carry the expected loads.

Figure 2 - Cyclic oxidation test



It is also essential to recognize that alloys will expand from 3/16 inch to ¼ inch per foot when heated from room temperature to 1800°F. The force of this expansion can damage either the alloy or the furnace structure if it is not properly provided for.

Characteristically, heat resisting alloys have poor thermal conductivity. As a result, the most frequent cause of failure is thermal fatigue resulting from high cyclic stress loading that accompanies temperature changes. The thicker the metal, the greater the fatigue.

Figure 1 illustrates this point. Two bars, one 3/8 inch and one ½ inch in diameter are shown after repeated quenching from 1500°F. The ½ inch bar (right), having approximately 78 percent more cross sectional area, was unable to absorb the repeated strain, and has a maze of inter-granular fatigue cracks. The 3/8 inch bar, however, remains sound when subjected to the same thermal cycling. Once again, this supports the statement: successful design is thin design.

Fabricability: The basic considerations that apply in forming or bending stainless steel are too complex to include here but they apply also to the handling of heat resisting alloys. Inasmuch as all heat resisting alloys are designed to be strong when they are hot, cold forming is recommended whenever possible. More good alloy has been lost in fabrication by improper heating to form than almost any other way.

Another consideration is weldability. Wrought heat resisting alloys are readily welded, using well established procedures. But to assure success, the designer has the responsibility (often overlooked) of specifying the proper filler alloy. If the welder is permitted to make his own selection of filler material an incorrect choice may be made through lack of information, and an inferior joint may result, seriously jeopardizing overall performance.

Considering these five factors simplifies alloy selection and energy-effective design becomes a reality. HT