Understanding Various Factors that Reduce Heat-Resistant-Alloy Component Life

Jason Wilson - Rolled Alloys, Temperance, Mich.

Choosing the optimum heat-resistant material for a given application will increase the useful component life and keep your maintenance costs under control. This article helps to identify the right material for the job and provides some things to watch for to avoid catastrophic failure.

Heat-resistant stainless steels and nickel-based alloys are commonly used for different furnace internals and carrying fixtures in the heat-treating industry. These components require periodic replacement due to a variety of factors. By understanding some of the more common causes for failure, it is possible to extend the life of these components through improved design, material selection, etc. With the alloy costs increasing significantly over the past three years, increasing the useful life of your components can help keep your maintenance costs in check.

Considerations for Materials Selection

Alloy fabrications typically end their life as a result of either attack by corrosion or a mechanical failure. Some of the following will be discussed in detail.

Common High-Temperature Failure Modes

Corrosion

- Oxidation
- Sulfidation
- Chloride/salts
- Metal dusting/carbon rot

Mechanical

- Creep
- Thermal expansion
- Embrittlement
- Thermal fatigue
- Thermal shock
- Molten-metal embrittlement

The two main criteria for materials selection should be: what is the maximum operating temperature of the alloy, and will it possess the necessary strength for the application? Alloy suppliers list the suggested maximum operating temperature for each alloy in our literature. This temperature is typically based upon when the rate of scaling from oxidation becomes unacceptable. It is not based on melting temperature. Most heat-resistant alloys have oxidation limits several hundred degrees below their melting points. Figures 1 and 2 provide suggested alloy temperature limits and show an example of what can occur when pushing an alloy beyond these limits.

It is also important to understand that the actual temperature of a muffle or radiant tube is hotter than both the temperature of the exiting parts or the furnace chamber. With this in mind, increased production through a furnace means the operating conditions for the muffle or radiant tubes have changed. The production parts may be seeing the same temperatures. To heat up the additional weight in the same time, however, more heat must be put into

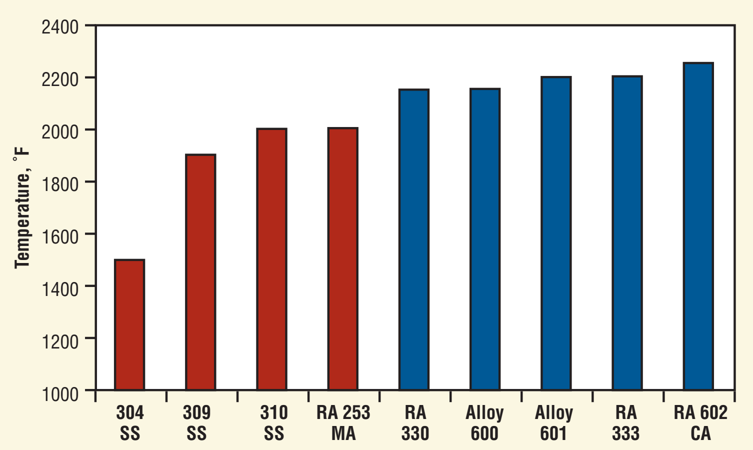

Fig. 1. Suggested temperature limits in air for various heat-resistant alloys. Red colors are stainless steels, and blue colors are for nickel-based alloys.

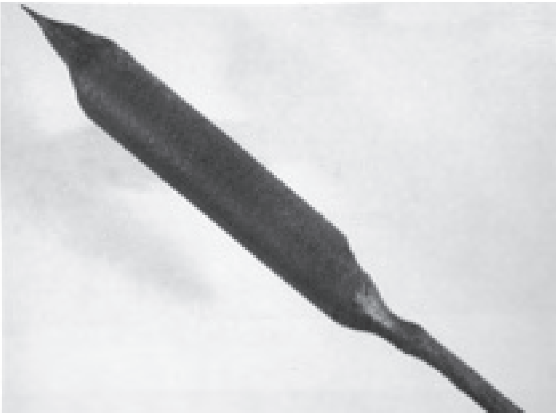

Fig. 2. 316L round-bar ¾ inch in diameter exposed to 1800°F in air atmosphere. 316L is suggested to be used only to 1500°F due to scaling. In contrast, its melting point is 2540°F.

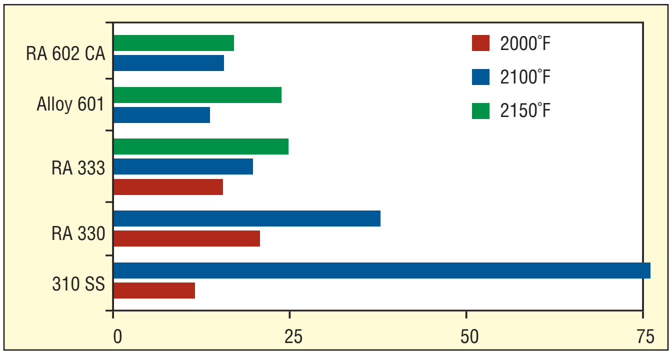

Fig. 3. Weight gain (mg/cm²) during cyclic oxidation testing. Samples cycled weekly to room temperature.

Table 1. Common Alloy Chemistries

Alloy	Similar Casting	Ni	Cr	Fe	Si	Other
446		-	25	73	0.5	
304		8	18	70	0.5	
309	HH	13	23	62	0.8	
310	HK	20	25	52	0.5	
RA 253 MA®		11	21	65	1.7	Ce, N
RA330®	HT	35	19	43	1.25	
RA333®	22H	45	25	18	1.0	Mo,Co,W
Alloy 601		61	21	14	0.2	
RA 602 CA®		63	25	9	0.03	Al,Zr,Ti
Alloy 600	HX	76	15	8	0.2	

the system either through the muffle wall or radiant tube. So although the process appears to be the same, the muffle or radiant tube is seeing tougher conditions, and this often means decreased life. Small increases in temperature do dramatically impact the properties of high-temperature alloys.

It is interesting to look at what an extra 100°F in metal temperature can do to material performance. From a scaling standpoint, if you go beyond the temperature capability of the alloy, they can scale at significantly faster rates. Figure 3 shows an example of scaling rates of various alloys. Note that 310 stainless is rated to 2000°F. At that temperature it has relatively low weight gain. At 2100°F, however, its oxidation rate is off the chart.

Perhaps more important is that the creep-rupture strengths of heat-resistant alloys decrease rapidly as temperatures increase. Table 2 shows stress-to-rupture strengths for various alloys at 1700-2000°F. Increasing the operating temperature of an alloy by 100°F decreases the strength on average 30-40%.

Using high-strength alloys and taking advantage of their high strength can lead to cost savings. Figures 5a and 5b show the original design of a coating retort with significant external reinforcement ribs. The higher strength of RA 602 CA allowed the fabricator to eliminate the external reinforcements completely. The simplified design is lower cost than the more complex alloy-600 fabrication, and the furnace load sees more even heat distribution, allowing better process control.

Carburization

Chromium, nickel and silicon are the three primary elements that provide an alloy resistance to the absorption of carbon. Nickel and silicon lower the maximum solubility of carbon and nitrogen. Carburization is normally an issue because highly carburized alloys become brittle. Above about 1% carbon, most wrought heat-resistant alloys have no measurable room-temperature ductility. This lack of ductility may result in the part fracturing and/or limiting the ability to repair, weld or restraighten the carburized fixture.

Metal dusting, also known as catastrophic carburization or carbon rot, is a metal wastage, not an embrittlement phenomenon. In the right environment (carbon-rich with temperatures around 1100°F), it appears that any alloy can eventually produce metal dust. Overall, there is disagreement regarding appropriate alloy selection. Generally, nickel alloys with high chromium contents and additions of silicon and/or alumina typically offer improved performance. In the steel heat-treating industry, experience has shown that RA333 and Supertherm are two of the best for resistance. In the petrochemical industry, RA 602 CA alloy is commonly used to upgrade from 800H. Since metal dusting typically occurs in a very localized area and these alloys can be expensive, it may be most cost effective to use these alloys for only the problem area while the remainder of the component is made of the original-construction material. For example, in Fig. 6, RA333 was used for the first 2 feet of a U-type radiant tube. This area passes through the refractory and is subject to metal-dusting attack. RA330 is used for the remainder of the tube.

Molten Salts

Attack by molten salts can be a significant issue. Probably the most extreme example

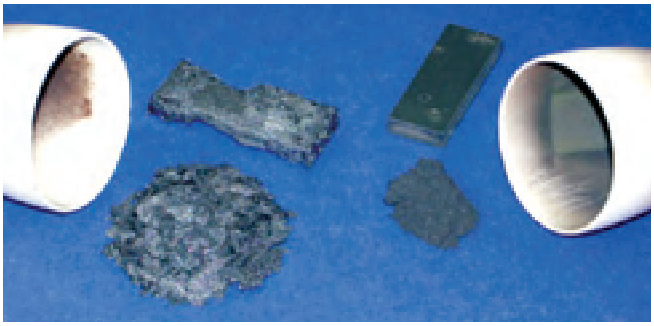

Table 2. 10,000 Hour, Average Stress for Rupture, psi

Alloy	1700°F	1800°F	1900°F	2000°F
RA310	940	660		
RA 253 MA	1,650	1,150	860	680
RA330	1,050	630	400	280
RA600	1,650	450	--	--
RA601	1,200	820	--	330
RA 602 CA	2,180	1,490	990	670

◀ (pictured left) Fig. 4. Scaling of alloy 600 (left) and RA 602 CA (right) samples after 3,000 hours at 2150°F. Both samples began as ¼" plate.

Figs. 5a. & 5b. Top of a coating retort made of 600 alloy with alternating reinforcement ribs of 600 and RA602 CA. The higher strength of RA 602 CA is evident in the close-up view. Retort wall temperatures are between 2000˚-2100˚F.

of this is the erratic service life of salt pots. From time to time the insufficient cleaning of spilled salt from the furnace chamber of a salt-pot furnace causes a rapid pot failure. The salt vapors that form in the chamber upon heating are very aggressive and cause a loose porous oxide scale to form on the surface. This scale is nonprotective and prone to rapid spalling.

In our experience, increasing nickel content aids resistance, whereas increased chromium levels can be detrimental. As a result, Alloy 600 (75Ni-15.5Cr) is commonly considered to have very high resistance and RA330 at 35Ni-19Cr is also considered to have good resistance. Each would still have very short life without proper cleaning prior to installation.

Thermal Expansion

One of the leading reasons for a high-temperature alloy to fail is distortion or fracture. It is important to understand that in comparison to mild steel, stainless steels and nickel alloys are poor conductors of heat. They also have higher rates of thermal expansion. Because of their low thermal conductivity, these alloys are more prone to uneven heating or hot spots.

The burner-can shown in Fig. 8 shows what can occur with uneven heating. During low fire the burner flame impinged on the walls of the burner-can. The shiny glazed scale where the can has distorted indicates

Fig. 7. Example of scaling happening on the outside of a salt pot after two weeks in service. The previous pot lasted over 15 years. The salt temperature was below 1300°F.

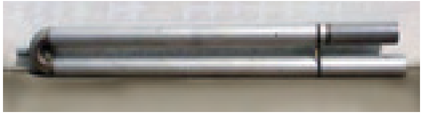

Fig. 6. U-type radiant tube made primarily from RA330 alloy but with RA333 for 2-foot section most prone to metal-dusting attack.

Fig. 8. This burner-can is a good example of what can happen when uneven heating occurs. In this case, flame impingement occurred during a low-fire condition.

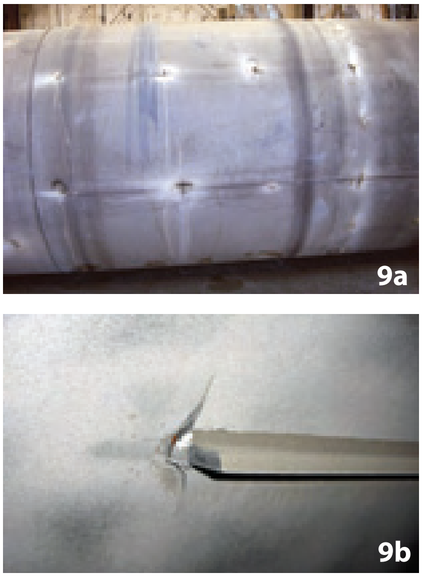

Fig. 9a. & 9b. Example of a calciner unit that suffered cracking of the shell. This was a result of temperature differentials between the shell and internal flights.

high heat exposure. The other areas of the can operated at much lower temperatures. The area with flame impingement was restrained from expanding by the cooler areas of the can. These cooler areas are also stronger because of their lower temperature. Since expansion of the hot spot was restricted, it buckled to relieve the stress.

In another example, a calciner shell suffered cracking that occurred in a definite pattern. This is shown in Fig. 9a. Cracks were found to occur at the ends of each internal flight as shown in Fig. 9b. The cause of this cracking is that the calciner is externally heated. The flights are heated by conducted heat from the shell and are in more contact with the cool product being processed through the calciner. As a result, the flights operate at a lower temperature than the shell. As the hotter, weaker shell tries to expand, the cooler, stronger flight restrains it. This results in the shell cracking under the stress. In this case, one suggestion would be to not solidly weld the flights. It is instead recommended to weld the flights to the shell only at the center, leaving the ends free so as not to restrict the shell from expanding and contracting. **IH**

253 MA is a registered trademark of Outokumpu Stainless. RA330 and RA333 are registered trademarks of Rolled Alloys. 602 CA is a registered trademark of ThyssenKrupp VDM.
Supertherm is a registered trademark of Duraloy Technologies Inc.

For more information: Jason Wilson is technical marketing manager for Rolled Alloys, 125 West Sterns Rd., Temperance, Mich. 48182; tel: 800-928-9482; e-mail: jwilson@rolledalloys.com; web: www.rolledalloys.com

Additional related information may be found by searching for these (and other) key words/terms via BNP Media SEARCH at www.industrialheating.com: nickel-based alloy, stainless steel, thermal expansion, embrittlement, thermal shock, radiant tube