Heat resistant alloys: Selection and failure avoidance

Heat resistant stainless steels and nickel-based alloys are commonly used in the petrochemical industry. They are also very important and widely used in metal treating, power generation, and incineration industries. 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, operation, and/or material selection, etc. With alloy costs rising significantly over the past few years, increasing the useful life of these components can dramatically reduce maintenance costs.

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Table 1: Common alloy chemistries

Wrought Material	Similar Casting	Ni	Cr	Fe	Si	C	Other
446		-	25	73	0.5	0.05	
304		8	18	70	0.5	0.05	
309	HH	13	23	62	0.8	0.05	
310	HK	20	25	52	0.5	0.05	
1.4841 (314)	HK	20	25	51	2.2	0.10	
253MA®		11	21	65	1.7	0.08	Ce, N
RA330®	HT	35	19	43	1.25	0.05	
RA333®	22H	45	25	18	1.0	0.05	Mo,Co,W
Alloy 601		61	21	14	0.2	0.05	
602CA®		63	25	9	0.03	0.20	2.2Al,Zr,Ti
Alloy 600	HX	76	15	8	0.2	0.04	

Considerations for materials selection

Alloy fabrications typically end their life as a result of either attack by high temperature corrosion or a mechanical failure. Listed are several common high temperature failure modes. The bolded topics shown are the focus of this article.

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

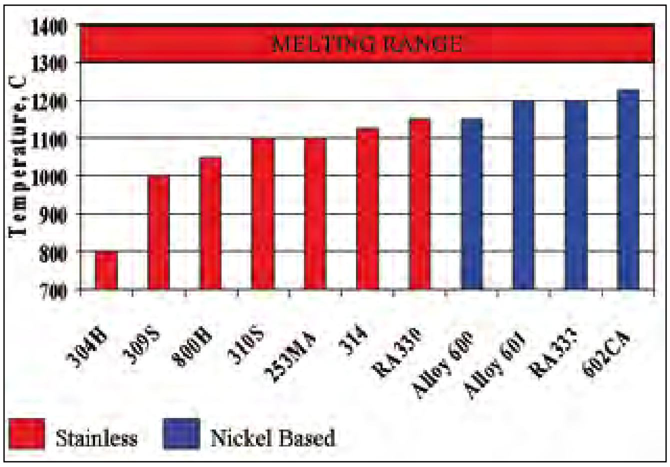
Mechanical
- Creep
- Distortion
- Embrittlement
- Thermal fatigue
- Thermal shock
- Molten metal embrittlement

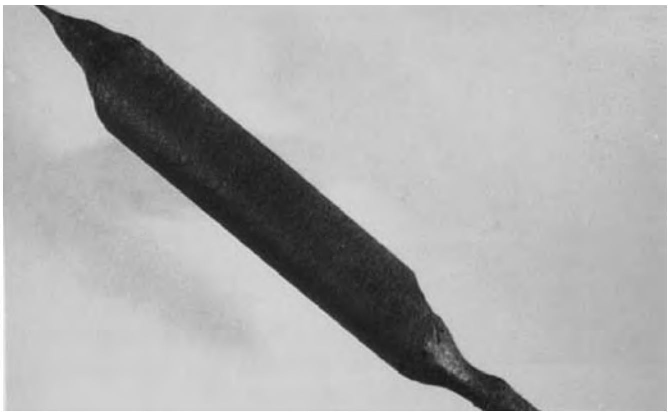
Understanding the limits

The first two criteria for materials selection should be what is the maximum operating temperature of the alloy and then does it possess the necessary strength for the application. Alloy suppliers like Rolled Alloys list the suggested maximum operating temperature for each alloy in their 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. Heat resistant alloys depend on the formation of an adherent protective oxide scale. This protective oxide scale is primarily formed by chromium in the alloy; however, they can be enhanced by silicon, aluminum and rare earth additions. At the suggested maximum temperature for each alloy, the oxide flakes off of the surface too rapidly and metal wastage will occur.

It is important to understand that the actual temperature of a muffle or calciner is normally hotter than the temperature of the exiting parts or powders. When the economy is good it is not unusual to demand greater production rates through a furnace. This means the operating conditions for the alloy muffle, calciner, etc. have changed. The production parts are seeing the same temperatures, however, to heat up the additional mass in the same time period more heat must be put into the furnace through the muffle or calciner wall. 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 dramatically impact the properties of high temperature alloys. It is interesting to look at what an extra 100°F (56°C) 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. An example of scaling rates of various alloys is shown. Note that 310 stainless is rated to 2000°F (1093°C). At that temperature it has relatively low weight gain, however at 2100°F its oxidation rate is off of the chart.

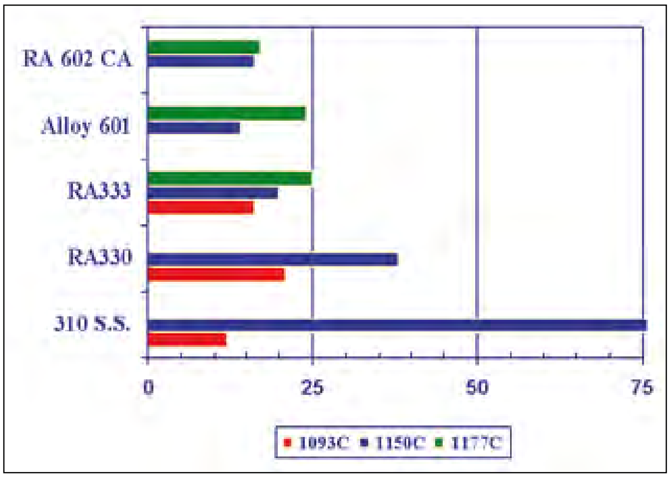
Suggested temperature limits in air for various heat resistant alloys. Red Colors are stainless steels and blue colors are for nickel-based alloys.

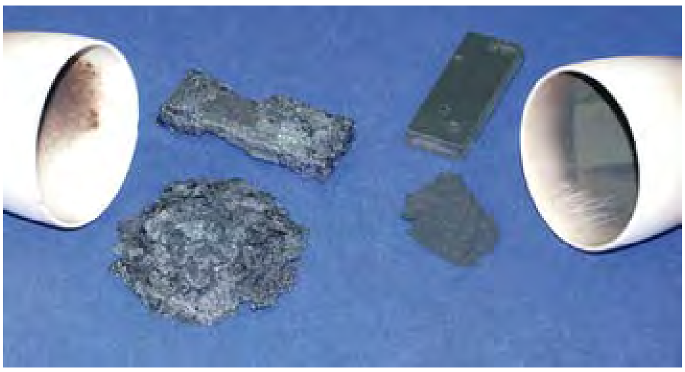




316L round bar ¾ inch in diameter exposed to 1800°F (982°C). Air atmosphere. 316L is suggested to be used only to 1500°F (816°C), due to scaling. In contrast its melting point is 2540°F (1343°C).

Weight gain (mg/cm²) during cyclic oxidation testing. Samples cycled weekly to room temperature. Total test time 3000 hours.





View of alloy 600 (left) and alloy 602CA (right) samples after 3000 hours at 2150°F (1177°C). Both samples began as ¼" inch (6.3 mm) plate.

Perhaps more important, is the fact that creep-rupture strength decreases rapidly as temperature increases. Creep-rupture properties must be considered for long-term service. At temperatures above 1000°F (538°C) they are a more accurate indicator of strength properties than short-term tensile data. Table 2 shows average stress to rupture values for various alloys at 1700-2000°F (927-1093°C). An increase in alloy temperature of 100°F (56°C) reduces strength on average 30-40%.

Table 2: 10,000 Hour, average stress for rupture, psi (MPa)[1]

Alloy	1700°F=927°C	1800°F=982°C	1900°F=1038°C	2000°F=1093°C
310 Stainless	940 (6.5)	660 (4.6)	-	-
253MA	1,650 (11.4)	1,150 (7.9)	860 (5.9)	680 (4.7)
Alloy 800H	1,900 (13.1)	1,200 (8.3)	-	-
RA330	1,050 (7.2)	630 (4.3)	400 (2.8)	280 (1.9)
Alloy 600	1,650 (11.4)	450 (3.1)	-	-
Alloy 601	-	1,200 (8.3)	-	620 (4.3)
602CA	2,180 (15.0)	1,490 (10.3)	990 (6.8)	670 (4.6)

High creep-rupture values are available in some of the newer alloy developments. There are a variety of ways that higher creep-rupture strength can be attained in heat resistant alloys. Alloy 800H relies upon a solution annealing treatment that results in a coarse grain structure in combination with aluminum and titanium additions[2]. Alloy 253MA relies primarily upon a 0.17% nitrogen addition[3]. Alloy 602CA relies primarily on a solution annealing treatment combined with a high carbon level, 0.2%[4].

Taking advantage of high strength alloys can lead to cost savings even if their cost per kilogram may be more. 253MA alloy is only 11% nickel yet it provides greater strength than 35% nickel, RA330 along with higher strength. In many applications operating below 2000°F (1093°C) this alloy is being considered to replace 309, 310, and some nickel alloys.

253MA corrugated boxes fabricated from 3mm sheet (11ga) replaced 309 and RA330 in this isothermal heat treating operation at 1750°F (954°F). The higher strength has extended fixture life over both materials.

1 Rolled Alloys Bulletin 100.
2 Special Metals Publication SMC 047 (2004 rev).
3 Andersson, "High Temperature Properties and Corrosion Resistance of a 21 Cr-11Ni Stainless Steel Alloyed with Silicon, Nitrogen, and Rare Earths", Paper 129, Corrosion 1979.
4 J. Wilson, D.C. Agarwal, "Case histories of successful application of alloy 602CA (UNS06025) in high temperature environments" paper 05423, Corrosion 2005.

253MA replaced type 310 stainless in this fluidized bed cyclone dip tube. That measures 8.5 ft (2.6 m) diameter and 23 feet (7 m) long and operates at 1600°F (871°C). 253MA lasts at least 6 years before distortion shown at right led to its replacement. 310 stainless required replacement every 2-3 years.

Photos in this article show two operations where 253MA has successfully been substituted in place of 309, 310, and RA330.

The figures below show the original design of a retort used in a furnace to apply aluminum rich coatings to gas turbine engine blades. The low strength of alloy 600 at 1975°F (1080°C) led to the addition of significant external reinforcement to combat distortion of the 3/8 inch (9.5 mm) sidewall. The higher strength of 602 CA allowed the elimination the external reinforcements completely. The simplified design was 35% lighter weight than the more complex alloy 600 fabrications. The simple 602CA design has a lower initial cost and has been lasting on average between 2-3 times as many cycles as the complex alloy 600 design. Other benefits are the furnace load sees more even heat distribution allowing better process control, less energy is wasted heating up the retort, and the excellent oxidation resistance of 602CA has reduced part rejection due to scale contaminating the finished parts.

Top overall of a coating retort made of 600 alloy with alternating reinforcement ribs of alloy 600 and 602CA. The higher strength of 602CA is evident in the close up view as is its better oxidation resistance. The 600 channel and retort wall have a roughened surface due to oxidation. The process inside the retort operates at 1975°F (1080°C).[5]

Distortion

One of the leading reasons for a high temperature alloy to fail is distortion or fracture. It is important to understand that relative to mild steel, stainless steels and nickel alloys are poor conductors of heat as shown in table 3. Because of their low thermal conductivity, these alloys are more prone to uneven heating or hot spots. They also have high rates of thermal expansion. Upon heating to 1832°F (1000°C), an RA330 pipe six meters long will expand in length by over 10 centimeters. These two factors make heat resistant alloys more prone to distortion and warpage upon heating and cooling.

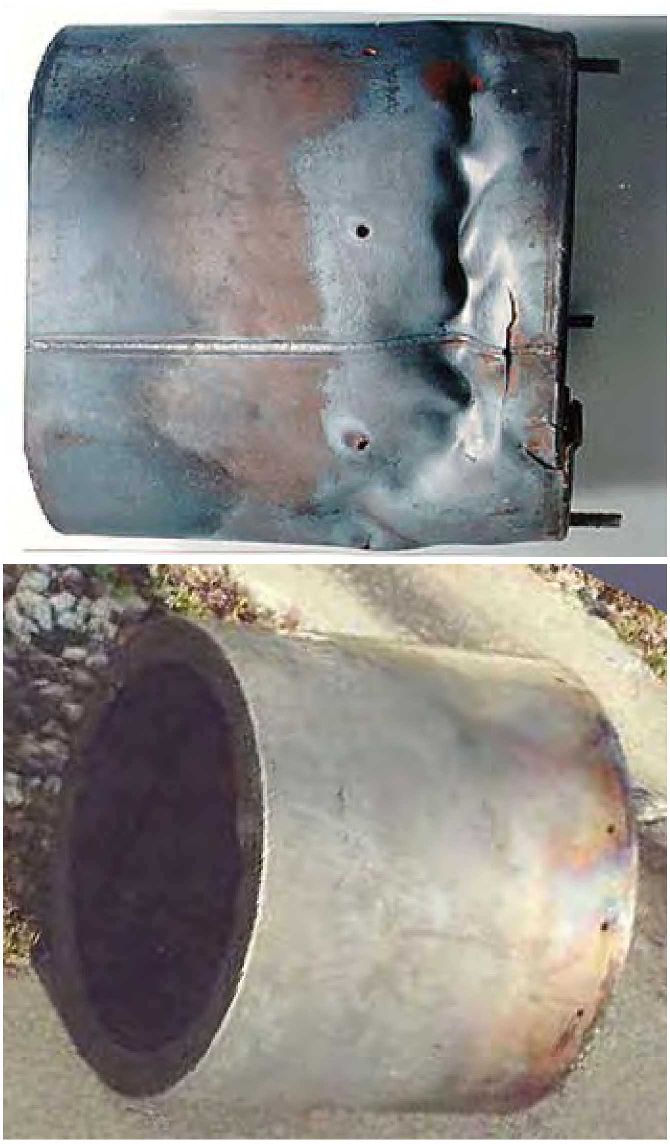
5 Rolled Alloys Case History #2032.

Table 3

	Thermal conductivity		Thermal expansion	
	BTU*ft/ft²*hr*°F	W/m*K	in/in°F*10^{-6}	m/m K*10^{-6}
Steel	26.6	46.0	6.5	11.7
309SS	7.4	12.8	8.8	15.8
RA330	7.2	12.5	8.3	14.9

Case 1

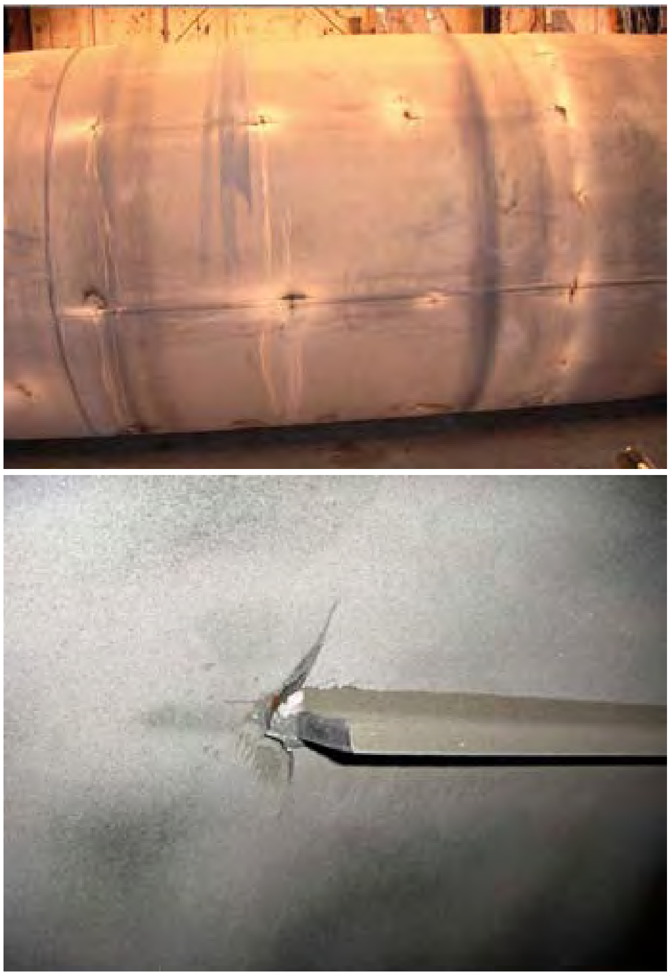
The burner can shown in Figure 8 shows what can occur with uneven heating. During low fire the burner flame impinged on the walls of the burner can. The shiny glazed scale where the can has distorted indicates high heat exposure. The other areas of the burner can operated at much lower temperatures. 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. As a result, the area of flame impingement collapsed.



This burner can made of 3mm (11ga) 253MA is a good example of what can happen when uneven heating occurs. In this case above, flame impingement occurred during a low fire condition. The photo below shows a can after use with a good temperature profile under normal operating conditions. Gas flow is right to left.

Case 2

A calciner shell suffered cracking that occurred in a definite patter (see photo). These cracks were found to occur at the ends of each internal flight (see photo). The cause of this cracking was temperature differentials between the shell and the flights. Gas-fired burners externally heated the calciner. The flights on the other hand were heated by energy conducted through the shell and were cooled by their more direct contact with the powders being processed. As a result, the flights operated at a lower temperature than the shell. As the hotter weaker shell tried to expand the cooler stronger flights restrained it. This resulted in the shell cracking under the stress at the ends of the flights. In this case, the suggestion was to refrain from solidly welding the flights. Instead weld the flights to the shell only at the center, leaving the ends free to expand or contract free of the shell.



Calciner shell fabricated from 3/8 inch (9.5 mm) plate that suffered cracking. This was a result of temperature differentials between the shell and internal flights.

Conclusions

1. Maximum operating temperatures for heat resistant alloys are based on scaling rates in air.
2. Small increases in temperature can greatly reduce alloy life due to reduced strength and/or increased scaling rates.
3. Allowing for thermal expansion is critical for high temperature designs.
4. There are many additional issues related to alloy selection. This article provides a basic education on some common concerns. Other issues not discussed can also greatly impact alloy life and need to be considered to properly select an alloy. ■