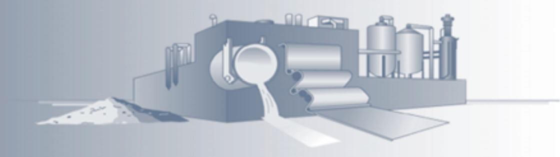

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A BestPractices Process Heating Technical Brief

Materials Selection Considerations for Thermal Process Equipment

U.S. Department of Energy

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Materials Selection Considerations for Thermal Process Equipment

Introduction

High-temperature metallic materials or alloys used in process heating equipment (furnaces, heaters, ovens, kilns, etc.) have significant effect on thermal efficiency, productivity and operating cost of the equipment. These materials are used in burners, electrical heating elements, material handling, load support, and heater tubes, etc.

A number of factors must be considered to select appropriate materials to improve energy efficiency of the equipment while extending their life at the minimum cost.

These factors include mechanical properties, oxidation or hot corrosion resistance, use of cast or fabricated components, and material availability.

Technical data describing the properties of heat-resistant alloys are necessary guides for selection. However, the behavior of alloys during long exposure to various high-temperature environments is complex. This behavior is not always completely predicted by laboratory tests alone. Service experience with high-temperature equipment is needed to judge the relative significance of the many variables involved.

Glossary of Terms

UNS	Unified Numbering System
EN	European Normal
W.Nr.	Werkstoff Nummer
Al	Aluminum
Cb	Columbium (Niobium)
Ce	Cerium
Co	Cobalt
Cr	Chromium
La	Lanthanum
Mo	Molybdenum
Si	Silicon
Ti	Titanium
Y_2O_3	Yttria (Yttrium Oxide)
W	Tungsten
Zr	Zirconium

Selection Criteria

Operating Temperature

Temperature is often the first—and sometimes the only—data point given upon which one is supposed to base alloy selection. However, one cannot successfully choose an alloy based on temperature alone. Nevertheless, one simple guide to alloy selection is an estimate of the maximum temperature at which a given alloy might have useful long-term engineering properties. Considering oxidation in air as the limiting factor, several common alloys, in plate form, rate as shown in Table 1. Thin sheets will have a lower limiting temperature because of proportionally greater losses from oxidation.

Thermal Stability

After long exposure to temperatures in the range of 1,100-1,600°F (590-870°C), many of the higher chromium alloys precipitate a brittle intermetallic compound known as sigma phase. Molybdenum contributes to this phase. Sigma reduces room-temperature impact strength and ductility. The quantity and morphology of the sigma phase determines severity of embrittlement. Usually the metal is brittle only near room temperature, and it retains reasonable ductility at operating temperatures between 600-1000°F (315-540°C). Higher nickel grades, such as N08811, N08330, N06600 or N06601, are not susceptible to embrittlement by sigma. Because of higher carbon content, which causes carbide precipitation, cast heat-resistant alloys lose ductility in service.

Strength

Creep-rupture properties at temperature are usually available from the various producers, and many alloys are covered by the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code.

Oxidation

Chromium is the one element present in all heat resistant alloys, and its protective chromia scale is the basis for high-temperature environmental resistance. Nickel is next in importance, then silicon, aluminum, and rare earths. Oxidation rates in service depend upon thermal cycling and creep, which increase scale spalling. In addition, contaminants, such as alkali metal salts, can damage the chromia scale grain size, which affects chromium diffusion rates, and the particular atmosphere involved also increases oxidation rate. Significant water vapor content usually increases oxidation rates.

Table 1. High Temperature Alloys (in order of increasing performance)

Alloy	Comments
Carbon steel, such as ASTM A 387 Grade 22 (2 1/4Cr, 1Mo)	This may be used to 1,200°F (649°C); above 950°F (510°C) 304H is stronger, and of course, more resistant to oxidation.
409, and 410S stainless (UNS S40900, S41008) 1200°F (650°C)	Limited by oxidation. Both are subject to embrittlement after several years of service above 600°F (315°C).
430 stainless (S43000), with useful oxidation resistance to about 1600°F (870°C)	Subject to embrittlement when exposed to the 600-1100°F (315-600°C) range.
304/304H & 316L stainless (S30400/S30409, & S31600), cast HF	This is limited by oxidation to 1,500°F (816°C). If product contamination by scale particles is a concern, consider 1,200°F (650°C) as limitation.
321 (S32100) stainless	This has an advantage of about 100°F (55°C) over 304, and is used to 1,600°F (1202°C).
309S (S30908), cast HH-2 (J93633)	Useful up to the 1,850-1900°F (1010-1038°C) range. Above 1900°F, oxidation performance becomes unsatisfactory.
Alloy 800HT® [1] (UNS N08811)	Much stronger, and somewhat more oxidation resistant. A practical upper use limit is about 2,000°F (1,093°C).
RA 253 MA® [2] alloy (UNS S30815)	Has superior oxidation resistance up to 2,000°F (1100°C). Above this temperature, the oxidation resistance may be adequate, but not exceptional
310 (S31008), and cast HK (J94204)	Very good oxidation resistance to 2,000°F (1,093°C), but drops off considerably by 2,100°F (1,150°C). The 310's strength is quite low at these temperatures.
RA330® [3] alloy (N08330, EN 1.4886)	Combines useful oxidation resistance and a fairly high melting point; it will tolerate rather extreme temperatures through 2,200°F (1,200°C). This grade is available in more product forms than almost any other high-temperature alloy. Applications include muffles, retorts, radiant heating tubes, bar frame baskets in heat treat, tube sheets, and tube hangers for petrochemical and boiler applications.
RA 353 MA® [4] alloy (S35315, EN 1.4854)	Has a melting point (solidus 2,480°F/1,360°C) similar to that of RA330, with better oxidation resistance. Experience with muffles, calciners, vortex finders, and cement kiln burner pipes show it to tolerate extreme temperature better than does RA330.
Alloy HR-120® [5]	One of the strongest available wrought alloys up to about 1,900°F (1040°C), and is used through 2,100°F (1,150°C).
RA333® [6] alloy (N06333)	In open-air use has a practical limit of about 2,200°F (1,204°C). Applications include retorts, rotary calciners, muffles for brazing, molybdenum, and tungsten oxide reduction.
625 (N06625)	Has high strength, but is limited by oxidation resistance to 1,800°F (980°C).
600 alloy (N06600)	A nickel-chromium alloy. Good oxidation resistance through 2200°F, good carburization resistance and ductility.
601 (N06601)	Is very oxidation resistant to 2,200°F (1,204°C). Applications include muffles, retorts and radiant heating tubes
RA 602 CA® [7] (N06025)	Extremely oxidation-resistant grade; one of strongest available at extreme temperature. Used through 2250°F. Applications include CVD retorts, vacuum furnace fixturing, rotary calciners
Alloy X (N06002)	Is designed for gas turbine combustors, in which hot gases continually sweep over the metal surface. Because of its 9% molybdenum content, this grade may be subject to catastrophic oxidation under stagnant conditions, or in open air above 2,150°F (1,177°C).
Alloy 617	Very strong. Typical uses include land-based gas turbine combustors and nitric acid catalyst support grids.
Alloy 230® [8]	Also a strong alloy, with excellent oxidation resistance and good retention of ductility after intermediate temperature exposure. Gas turbine combustors, nitric acid grids, and CVD retorts are some applications of this alloy.
Supertherm® [9], cast 26Cr 35Ni 5W 15Co	Under various trade names, is suited for extreme temperature conditions. The cobalt content is sufficient to minimize high-temperature galling wear when in contact with NiCrFe alloys.

Carburization

Chromium, nickel, and silicon are three major elements that confer resistance to carbon absorption. Nickel and silicon lower the maximum solubility of carbon and nitrogen. Carburization is usually of concern, because highly carburized alloys become brittle. Above about 1% carbon content, most wrought heat-resistant alloys have no measurable ductility at room temperature. Metal dusting, also known as catastrophic carburization or carbon rot, is metal waste, not embrittlement. In the right environment, it appears that any alloy can eventually metal dust. Disagreement exists regarding appropriate alloy selection. In the steel heat-treating industry, experience has shown that RA333 and Supertherm are two of the best choices, while 602 CA performs well in some petrochemical applications. However, 310 stainless has been used in petrochemical metal dusting environments. Alloys such as N08830 and N08811 do not perform well in metal dusting environments.

Sulfidation

Low or moderate nickel with high chromium content minimizes sulfidation attack at high temperatures. With the exception of alloy HR-160, less than 20% nickel content is preferred.

Fabricability

Typically, fabricability is not a significant issue for conventionally melted wrought alloys. Grades that are strengthened by oxide dispersion, such as MA956®, offer unmatched strength and oxidation resistance at extreme temperatures, but are difficult to fabricate by conventional means.

Design

Allowable stresses are often based on ASME design codes. For most thermal processing equipment, design stress is either one-half of the 10,000-hour rupture strength, or one-half of the stress to cause a minimum creep rate of 1% in 10,000 hours. Above about 1,000°F (540°C), creep or rupture is the basis for setting design stresses. At this temperature, materials are no longer elastic, but deform slowly with time.

Thermal Expansion

A major cause of distortion and cracking in high-temperature equipment is failure to adequately address the issue of thermal expansion, and differential thermal expansion. Temperature gradients of only 200°F (110°C) are sufficient to strain metals beyond the yield point.

Molten Metals

In industrial applications, low-melting metals such as copper and silver braze alloys, zinc, and aluminum cause problems. As a rule of thumb, low-melting metals attack the higher nickel alloys more readily than low-nickel or ferritic grades.

Galling

Austenitic nickel alloys tend to gall when they slide against each other. At elevated temperatures, cobalt oxide tends to be somewhat lubricious. Cobalt or alloys with high cobalt content, such as cast Super-therm, are resistant to galling at red heat. For heat treat furnace applications up through 1650°F, Nitronic® 60[10] (S21800) has resisted galling well.

Cast Versus Wrought Heat Resistant Alloys

The alloys are offered in two forms: cast form and wrought form. Each has advantages and disadvantages for use in process heating, as shown in Table 2.

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[1] Registered trade name of Special Metals, Inc.
[2] Registered trade name of Outokumpu
[3] Registered trade name of Outokumpu
[4] Registered trade name of AvestaPolarit
[5] Registered trade name of Haynes International
[6] Registered trade name of Rolled Alloys
[7] Registered trade name of ThyssenKrupp VDM
[8] Registered trade name of Haynes International
[9] Registered trade name of Duraloy Technologies, Inc.
[10] Registered trade name of AK Steel Corporation

Table 2. Comparison of Cast and Wrought Alloys

Alloy	Advantages	Disadvantages
Cast	Inherently greater creep strength	Embrittlement frequently occurs in service, making weld repair difficult
	Availability of shapes that are inconvenient to fabricate	May have soundness issues, such as porosity, shrink and surface integrity
	Chemistries not available as wrought alloys	May incur high costs for creating patterns, if only a few pieces are needed
	Some 35% and 50% chromium castings only available as castings	Delivery time may be long even if only a few pieces are needed
		Cast parts may be thicker and heavier than the equivalent fabrication. This increases the dead weight that is heat treated, and reduces efficiency of thermal transfer through the wall.
Wrought	Availability of broad range of section thicknesses. Wrought alloys are available as thin as foil.	Creep strength—few wrought alloys match the high strength of heat-resistant alloy castings. This must be considered in product design, where creep rupture is a concern.
	Thinner sections permit significant weight reduction	Composition—alloys such as 50Cr 50Ni, 28Cr 10Ni or 35Cr 46Ni, all with excellent hot corrosion and/or carburization resistance, are available only as castings.
	Smooth surface helps avoid focal point for accelerated corrosion by molten salts or carbon deposits	
	Usually free of the internal and external defects, such as shrink and porosity, found in castings	
	Availability—fabrications are quickly procured, using stock materials, which minimizes down time.	

Table 3. Material (Alloy) Composition

Nominal Chemistry, Ferritic Alloys

Alloy	Unified Numbering System (UNS)	European Normal/ Werkstoff Nummer EN/W.Nr	Chromium (Cr)	Silicon (Si)	Aluminum (Al)	Titanium (Ti)	Carbon (C)	Other
410S	S41008	1.4000	12.0	0.30	--	--	0.05	--
430	S43000	1.4016	16.5	0.50	--	--	0.08	--
MA956® [11]	S67956	--	19.4	0.05	4.5	0.4	0.02	$0.5Y_2O_3$
446	S44600	1.4763	25.0	0.50	--	--	0.05	--

Nominal Chemistry, Fe-Cr-Ni Alloys, Nickel 20% and under

Alloy	UNS	EN/W.Nr	Cr	Nickel (Ni)	Si	C	Nitrogen (N)	Other
304H	S30409	1.4301	18.3	9	0.5	0.05	--	70Fe
RA253 MA®	S30815	1.4835	21	11	1.7	0.08	0.17	0.04Ce 65Fe
309S	S30908	1.4833	23	13	0.8	0.05	--	62Fe
310S	S31008	1.4845	25	20	0.5	0.05	--	52Fe

Nominal Chemistry, Fe-Ni-Cr Alloys, Nickel 30% to 40%

Alloy	UNS	EN/W.Nr	Cr	Ni	Si	C	Other
800 HT®	N08811	--	21	31	0.4	0.06	45Fe 0.6Ti 0.4Al
803	S35045	--	25.5	34.5	0.7	0.07	37Fe 0.4Ti 0.3Al
RA330®	N08330	1.4886	19	35	1.2	0.05	43Fe
RA353 MA®	S35315	1.4854	25	35	1.2	0.05	36Fe 0.16N 0.05Ce
HR-160® [12]	N12160	--	28	36	2.8	0.05	30Co 2Fe 0.5Ti
HR-120®	N08120	--	25	37	0.6	0.05	35Fe 0.7Cb 0.1Ti

Table 3. Material (Alloy) Composition (continued)

Nominal Chemistry, Ni-Cr-Fe Alloys, Nickel 45% to 60%

Alloy	UNS	EN/W.Nr	Cr	Ni	Si	C	Other
RA333®	N06333	2.4608	25	45	1	0.05	3Co 3Mo 3W 18Fe
617	N06617	2.4663	22	54	0.03	0.08	12.5Co 9Mo 1Al 0.4Ti 1Fe
230®	N06230	--	22	60	0.4	0.10	14W 1.5Mo 0.3Al 0.02La

Nominal Chemistry, Nickel over 60%, 15% to 25% Chromium

Alloy	UNS	EN/W.Nr	Cr	Ni	Si	C	Other
601	N06601	2.4851	22.5	61.5	0.2	0.05	1.4Al 14Fe
RA 602 CA®	N06025	2.4633	25	63	--	0.2	2Al 0.1Y 0.08Zr 9.5Fe
214™ [13]	N07214	--	16	76	--	0.04	4.5Al 0.005Y 3.5Fe
600	N06600	2.4816	--	15.5	76	0.2	0.08 0.2Ti 8Fe

Nominal Chemistry, Cast Heat Resistant Alloys

Alloy	UNS	EN/W.Nr	Cr	Ni	Si	C	Tungsten (W)	Cobalt (Co)	Other
HC	J92605	--	28	2	0.8	0.3	--	--	67Fe
HD	J93005	--	29	5	1.5	0.4	--	--	63Fe
HE	J93403	1.4339	28	9	1.5	0.3	--	--	61Fe
HF	J	--	21	10	1.4	0.3	--	--	67Fe
HH-2	J93633	1.4837	25	13	1	0.3	--	--	60Fe
HI	J94003	--	28	16	1	0.4	--	--	54Fe
HK	J94204	1.4840	25	20	1.4	0.4	--	--	54Fe
HL	J94614	--	30	20	1.4	0.4	--	--	47Fe
HN	J		21	25	1.4	0.4	--	--	52Fe
Ten-X	--	--	20	30	1.4	0.4	5	8	35Fe
HT	J94605	--	17	35	1.7	0.5	--	--	44Fe
HU	J95405	1.4865	18	38	1.7	0.5	--	--	40Fe
HP	J95705	1.4857	26	35	1.3	0.5	--	--	36Fe
MO-RE® 1 [14]	--	--	26	36	1	0.45	1.6	--	33
Supertherm® [15]	--	--	26	35	1.5	0.5	5	15	13Fe
22H® [16]	--	2.4879	28	48	1	0.5	5	--	16Fe
Super 22H [17]	--	--	28	48	1	0.5	5	3	13
MO-RE® 40MA	--	--	35	46	1	0.45	--	--	14Fe 1.3Cb
HX	N06006	--	17	66	2	0.5	--	--	13Fe
IC-221M	--	--	7.7	81	--	0.04	--	--	8Al 1.3Mo 1.7Zr

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Composition of Alloys

Table 3 provides composition of commonly used alloys for industrial heating equipment. The alloy composition contains several elements which are added into iron. The percentage of the elements in the alloy are shown in Table 3.

Acknowledgements

Special thanks to Dr. James Kelly of Rolled Alloys and Arvind Thekdi of E3M, Inc., for their contributions to this Technical Brief.

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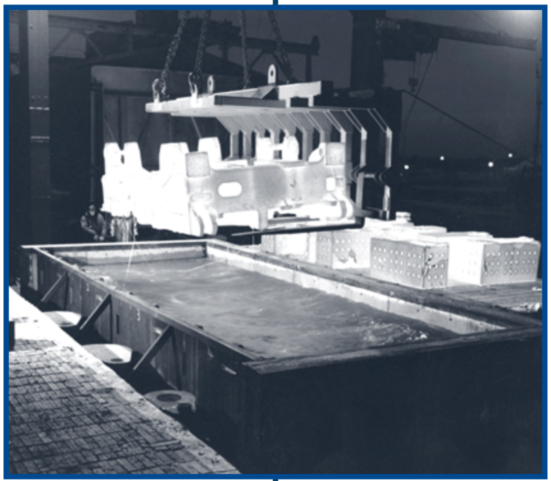

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DOE/GO-102004-1974
November 2004