A division of EMVAfrica

SELECTING ALLOYS FOR HIGH TEMPERATURE APPLICATIONS

The selection of material for each application is often a compromise between demands on mechanical strength, structure stability and corrosion resistance.[1]

In this e-Book you will learn about the parameters than can affect the reliable performance of metals intended for high temperature service.

INTRODUCTION

Stainless steels and nickel alloys are widely used because of their resistance to aqueous corrosion but there are also grades in both families of alloys that are most useful for high temperature service in a range of industrial applications. Generally "high temperature" is considered to be above 500°C as it is above this point that creep becomes a mechanical property determinant. Each grade may have its own useful temperature limit, but very few may be used at 1200°C as this approaches the melting point of many industrial metals.

In this review, the temperature range in focus is 500 to 1200°C

INTRODUCTION

Refractory Metals such as tungsten and molybdenum have much higher melting points than 1200ºC. However they react very readily with oxygen, carbon etc and thus they can only be used at elevated temperatures in an inert atmosphere or in a vacuum and are not suitable for most industrial high temperature applications.

*The more common and readily available alloys for use at high temperature are listed in **Table 1**.*

It does not include grades that are designed for the most extreme service conditions. Examples of such applications are:

- *In respect of strength, this includes applications such as high temperature turbines and bolting.*
- *In respect of corrosion resistance, waste incineration results in complex high temperature corrosion conditions and along with metal dusting application specific alloys may be needed.*

Table 1: Stainless Steels and Nickel Alloys used for High Temperature Applications

GRADE	NOTE	UNS No	%C (max)	%Cr	%Ni	%Mo	Other	COMMENT
446	a	S44600	0.2	25.0	0.5		N	A general purpose heat resisting grade
310S	b	S31008	0.08	25	20.5			A widely used grade having useful strength and oxidation resistance
316Ti		S31635	0.08	17.0	12.0	2.5	Ti	A variant of 316 but with improved elevated temperature strength
253MA		S30815	0.1	21.0	11.0		Si,N,Ce	A grade with superior creep strength and corrosion resistance at temp
Alloy 800H	c	N08810	0.1	21.0	32.5		Cu,Al,Ti	A higher nickel grade used extensively in the petro-chemical industry
Alloy 600		N06600	0.15	15.5	72 min			A general purpose nickel alloy suitable for a wide range of applications
Alloy 625		N06625	0.1	25.0	58 min	9.5	Al,Ti,Zr,Y	A heat treatable nickel alloy with superior creep strength
Alloy 601		N06601	0.1	23.0	60.0		Al,Cu	A nickel alloy with excellent oxidation resistance

Ferritic Stainless Steels **Austenitic Stainless Steels** **Nickel Alloys**

NOTES:

a – alternatives are 4C54 and 1.4762

b – lower carbon variant of 310; similar to 314

c – variants are Alloy 800 and Alloy 800HT

HIGH TEMPERATURE STRENGTH

Creep data is not presented by producers as guaranteed but rather as "typical". It is determined by mills, academia and research institutions to provide guidelines for users

From approximately 500°C and above, a form of mechanical damage known as creep may occur and this may become the primary mechanical property consideration in selecting alloys for reliable performance. The phenomenon of creep is a function of temperature, stress and time. It is recognition of the fact that at elevated temperatures engineering alloys will deform over time at a stress lower than the guaranteed minimum proof strength.

The nature of mechanical deformation is such that the addition of alloying elements will always have a strengthening effect when compared with pure metal. This is true at high temperatures as well and specific elements may have a more pronounced effect than others in this regard. Molybdenum, tungsten, niobium and tantalum may be used to increase creep strength by a solid solution mechanism.

Precipitation strengthening is a second common method for enhancing the strength of metals for use at ambient but also elevated temperatures. These precipitates in the structure result from the addition of aluminium, titanium and copper to stainless steels or aluminium plus titanium or niobium in nickel alloys.

Carbon, an "undesirable" in stainless steels and nickel alloys because of the effect that it may have on corrosion resistance if carbides are able to form, is known to improve creep strength. Thus there are specifications for "H-Grades" eg 316H in which the carbon content is controlled above a certain value.

HIGH TEMPERATURE STRENGTH

Nitrogen will have benefits similar to carbon in respect of creep strength. The addition of titanium to create stabilised grades such as 321 and 316Ti, provides a good compromise by allowing carbides to form thereby enhancing creep strength, without denuding the chromium and thereby damaging corrosion resistance.

Comparative high temperature strength data for the alloys listed is not readily available. EN 10095 contains information that covers most of the grades OR their nearest alternatives and **Table 2** has been drawn up using this unless otherwise indicated.

High temperature bolting is a specific application in which creep strength is most important. Two Grades of stainless steel which offer high strength and are used for this application are 1.4913 and 1.4923. These are martensitic stainless steels and they display good oxidation resistance up to 600ºC.

More details are in our Alloy Insights on these grades »

Table 2: Stainless Steels and Nickel Alloys used for High Temperature Applications Property Data (for guidance only)

GRADE	UNS No	EN	0.2% Proof (MPa) #	Creep Rupture in 10^5 hrs at 600°C (MPa)	Creep Rupture in 10^5 hrs at 800°C (MPa)	Expansion Coeff. between 20°C & 800°C (10^{-6}/°K)
446	(S44600)	1.4762	280			12.5
310S	(S31008)	1.4845	210	80	7	18.5
316Ti	S31635	1.4571	200 *	118 *	14 *	
253MA	S30815	1.4835	310	88	15	19.0
Alloy 800H	N08810	1.4876	170	114	21	17.5
Alloy 600	N06600	2.4816	240	97	17	16.2
Alloy 625	N06625	2.4856	330	302 **	34 **	16.8
Alloy 601	N06601	2.4851	205	156	17	16.5

Ferritic Stainless Steels **Austenitic Stainless Steels** **Nickel Alloys**

NOTES:

At Room Temp
* from ECCC Data sheet
** VDM Metal Data Sheet: VDM Alloy 625 (grade2)

HIGH TEMPERATURE CORROSION RESISTANCE

High temperature service environments may be categorised according to oxygen activity as oxidising, if there is excess free molecular O_2, or reducing if there is very low oxygen activity. Generally reducing conditions are the more corrosive. The corrosion rate will be a function of the environmental conditions and temperature.

There are a number of mechanisms by which high temperature corrosion may take place and the more common ones are listed in **Table 3**. The terminology reflects the primary corrodent but industrial environments usually contain a mix of the aggressive species and thus the damage that arises may a reflect their synergistic effect.

Table 3

HIGH TEMPERATURE CORROSION MECHANISMS (Ref 2)
Oxidation
Sulphidation
Carburization & Metal Dusting
Nitridation
Halogen Corrosion
Molten Salt Corrosion
Molten Metal Corrosion
Ash/ Salt Deposit Corrosion

Ref.2: High Temperature Corrosion of Engineering Alloys - G Y Lai. ASM International, 1990

HIGH TEMPERATURE CORROSION RESISTANCE

OXIDATION

THE GOOD:
The creation of a protective oxide scale on the metal's surface relies on oxidation.

THE BAD:
Conditions may be such that the extent of the oxidation is excessive and hence destructive.

OR:
oxidation may also participate in the overall reaction with other mechanisms.

Oxidation is the most important of these corrosion reactions. It is essential in transforming chromium, the element that makes stainless steel "stainless", into an adherent protective oxide scale which can ensure resistance to high temperature corrosion. Aluminium and silicon are also used to enhance the protective nature of the scale.

HIGH TEMPERATURE CORROSION RESISTANCE

The damaging effect of carbon in high temperature service environments arises from its diffusion into the metal via the grain boundaries which results in carbides, particularly with chromium. Not only does this reduce the metals ability to form a protective scale but it can also result in actual metal loss - a phenomena known as metal dusting. This may occur in the chemical and petrochemical industries

Sulphidation is generally deleterious because the sulphur present may affect the integrity of the protective scale and because it may also form low melting point sulphides with alloying elements most notably nickel. Chlorides, other halides, nitrogen and molten metals and salts may all cause significant corrosion phenomena and they should be viewed as potential risks when faced with material selection decisions. Similarly oxygen and carbon may participate in corrosion reactions if they are present as steam and carbonaceous compounds.

Long term, reliable resistance to attack requires that any protective scale that does form be able to withstand thermal cycling and mechanical loads both of which can cause spalling of the layer.
To this end alloy developers have established that the addition of rare earths (viz.: Ytrium, Lanthanum and Cerium) into the alloy improves the adherence of the layer.

MICROSTRUCTURAL STABILITY

Thermal stability, the retention of properties at high temperatures over time is a manifestation of a stable microstructure and is an important characteristic of alloys intended for service under these conditions. It is noteworthy that many precipitates that may form in stainless steels and nickel alloys while in service are undesirable.

They may be embrittling or affect corrosion resistance and these precipitates must not be confused with those that result from deliberate alloying element additions intended to increase strength. The dualism of carbide precipitates illustrates this point. On the one hand they may result in an increase in the creep strength of the alloy but on the other they may denude the metal of chromium and thereby reduce corrosion resistance.

What can I use in a furnace operating at 900°C?

Knowing the temperature is not enough!!!

CONCLUSIONS

The question above is often asked without describing the operating conditions and strength requirements and in the preceding sections the importance of this further information is highlighted. Further practical considerations are:

- **Thermal cycling.** The expansion and contraction that may result from this may have a two-fold effect: the cyclical stresses that result may give rise to thermal fatigue and the protective scale on the metals surface may spall off, giving rise to attack of the metal beneath.

- **Design and Fabrication.** In keeping with good practice points of stress concentration should be avoided. Because of the difference in the coefficients of expansion, the joint of ferritic and austenitic grades must be avoided.

- **Temperature measurement.** There are applications in which the temperature measured may be lower than that to which the metal is exposed. eg. Externally heated muffles and radiant tubes.

- **Hydrogen and natural gas.** The transition from coal and oil as fuels or raw materials to natural gas and hydrogen will result in a change in the environment that the materials of construction are exposed to and this may result in unexpected corrosion phenomena.

Selecting materials for high temperature applications needs to take into account more parameters than it appears at first.

We welcome the opportunity to be of assistance.

A division of EMVAfrica

MULTI Alloys

CONTACT US

T: + 27 (0) 11 466 2480

F: + 27 (0) 11 466 1692

E: sales@multialloys.co.za

www.multialloys.co.za

REFERENCES:

1 Stainless Steel Tubes for High Temperature Application. – Alleima

2 High Temperature Corrosion of Engineering Alloys - G Y Lai. ASM International, 1990

3 BS EN 10095:1999

4 European Creep Collaborative Committee Data, 2005