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Materials Properties Database for Selection of High-Temperature Alloys and Concepts of Alloy Design for SOFC Applications

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Abstract

To serve as an interconnect / gas separator in an SOFC stack, an alloy should demonstrate the ability to provide (i) bulk and surface stability against oxidation and corrosion during prolonged exposure to the fuel cell environment, (ii) thermal expansion compatibility with the other stack components, (iii) chemical compatibility with adjacent stack components, (iv) high electrical conductivity of the surface reaction products, (v) mechanical reliability and durability at cell exposure conditions, (vii) good manufacturability, processability and fabricability, and (viii) cost effectiveness. As the first step of this approach, a composition and property database was compiled for high temperature alloys in order to assist in determining which alloys offer the most promise for SOFC interconnect applications in terms of oxidation and corrosion resistance.

The high temperature alloys of interest included Ni-, Fe-, Co-base superalloys, Cr-base alloys, and stainless steels. In the US alone, there are hundreds of commercial compositions produced, over 250 of which are listed in Appendix A. Two initial criteria (oxidation resistance and oxide scale electrical conductivity) were used to reduce the list of alloys to manageable proportions. Thermal expansion and fabrication characteristics were then considered to further reduce the list of stainless steels. Due to their outstanding oxidation resistance and their potential to be used in SOFC components that can exclude alumina scales from the stack electrical path, alloys with a sufficient amount of aluminum were classified into a separate alumina-forming alloy category. The down-selected compositions (approx. 130 in number) and their characteristics and/or applications are listed in the Selected Alloy Compositions tables (Appendix B).

Following the down-selection of alloy compositions, materials properties of interest corresponding to the their functional requirements in SOFC stacks were compiled in a tabular form (Appendix C). For comparison, the properties of selected noble metals and intermetallics were also collected and compiled and are listed in a separate table in Appendix C.

Analysis of the pertinent literature indicated that, for a wide variety of alloys, there remains a lack of information on specific materials properties. Also, we have observed a large scatter in the reported database. For those cases, we employed general alloying principles as a tool of choice to approximate the unavailable data and to evaluate the reliability and consistency of collected data.

Though numerous high temperature alloys look promising, it is anticipated that there will be few, if any, "off the shelf" alloy compositions which could completely satisfy the materials requirements as an interconnect, especially for a long term in a specific SOFC design. Therefore, some concepts of alloy design, including composition, constitution, and structure, as well as their effects on properties relevant to SOFC applications, are elaborated in an attempt to provide guidance for modification of current compositions and development of new alloys.

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I. Introduction

Over the past several years, advances in planar anode-supported cell designs, along with improvements in the cell component materials and fabrication processes, have led to a steady improvement in the electrical performance, performance stability and reliability of planar SOFCs. The use of thin electrolytes and advanced cell electrode configurations and materials has led to a steady reduction in the operating temperatures to the 800ºC range or lower, without compromising the electrical performance or reliability.

Both metallic and ceramic interconnect materials have been used in SOFC stacks to demonstrate the feasibility of relatively long term operation of planar cells. Results indicate that although electronically conducting ceramic current collectors demonstrate superior chemical and structural stability; they remain very expensive and difficult to fabricate. Metallic current collectors, on the other hand, show surface oxide formation, increase in resistance and contamination of adjoining cell components. Metallic current collectors, however, remain highly cost effective and easy to fabricate when compared with ceramic counterparts.

In a planar SOFC configuration, the current collector / bipolar gas separator, as the name indicates, acts as a separator for the fuel and the oxidant gases and also serves as a current collector between cells. The fuel gas environment, consisting of H_2, H_2O, CO, CO_2, CHx, etc., has a low oxygen partial pressure (Log PO_2 (atm) = -14 to -20) and high carbon activity, while the oxidant gas environment usually consists of air. Exposure to this dual environment leads to oxidation and corrosion of metals and alloys resulting in the formation of various corrosion products. Bipolar separators also are exposed to peripheral gas seals (glass or compressive) and may experience chemical interaction with the seal materials.

Until recently, the leading candidate material for the SOFC interconnect was electronically conducting doped lanthanum chromite, $LaCrO_3$, a ceramic which could easily withstand the 1000°C operating temperature of an electrolyte or air electrode-supported SOFC design. CVD-EVD as well as high temperature sintering techniques were initially used for the fabrication of dense interconnections. Liquid phase sintering and dopants were also investigated to promote sintering at lower temperatures. However, difficulties with obtaining high-density chromite parts at reasonable sintering temperatures persisted. It was also found that the chromite interconnect tended to partially reduce at the fuel gas/interconnect interface, causing the component to warp and the peripheral seal to break. Development of the lower temperature anode supported cells which utilize nickel-based anode supports, thin electrolytes and highly active cathode structures have caused lanthanum chromite to be supplanted by metallic interconnects as the interconnect material of choice. Compared to doped lanthanum chromite, high temperature metallic materials also offer advantages such as improved manufacturability, significantly lower raw material and fabrication costs, and higher electrical and thermal conductivity. However, for a metallic alloy to be considered as a candidate material for the interconnect, it must satisfy the following requirements:

- Good surface stability (resistance to oxidation, sulfidation, and carburization) in both cathodic (air) and anodic (fuel gas plus water vapor) atmospheres during isothermal and thermal cyclic operations.

- Thermal expansion matching to the other stack components (as least for a rigid seal design).
- Chemical compatibility with other materials in contact with the interconnect such as seals and cell materials.
- High electrical conductivity through both the bulk material and in-situ formed oxide scales.
- Mechanical reliability and durability at the device's operating temperature.
- Strong adhesion or bond strength between the as-formed oxide scale and the underlying alloy substrate.
- Good manufacturability.

While there is a general agreement among the researchers in the SOFC technology development area that a suitable metal-based SOFC interconnect is needed for the overall cost reduction and faster start up, there is no agreement as to what alloy system might form the basis for this sub-component. Furthermore, there is no conclusive study that has been published in the open literature on suitable "lower" temperature SOFC interconnect materials that could serve as a reference. Long term degradation issues such as oxidation, carburization, sensitization, localized grain boundary penetration and oxide scale spallation still remain unresolved for a variety of alloys during their long term exposure under fuel cell operating conditions. The time, effort, and expense of developing a new alloy also needs basic understanding of the above degradation processes.

Considering the above materials requirements, oxidation-resistant alloys and several noble metals, such as platinum (including surface coatings), could be initially considered as potential candidates. The high cost of platinum and other noble metals, however, preclude their use as an interconnect in planar SOFCs. The remaining choices would be high temperature alloys that demonstrate oxidation resistance at elevated temperatures. The high temperature alloys of interest include Ni-, Fe- and Co-base superalloys, Cr-base alloys, and the stainless steels.

In the US alone, hundreds of commercial high temperature alloy compositions remain available for consideration for SOFC applications. To choose the best candidates for SOFC applications, and provide a reference for future research and development, the establishment of a materials database for the alloys of interest appeared to be mandatory.

As the first step to build the materials database for high temperature alloys, hundreds of commercial compositions, as listed in Appendix A, were collected from sources including textbooks, handbooks, electronic databases and producer Internet homepages. Both the alloy name and its UNS (Unified Numbering System) No., developed jointly by the U.S. Society of Automotive Engineers (SAE) and the American Society of Testing and Materials (ASTM), are listed with its composition. As the first cut, a selection criterion involving the content of critical elements (Cr, Al) in the alloys was established and applied to reduce the original composition lists to manageable proportions. The selected compositions with their characteristics and traditional applications are tabulated in Appendix B. The properties relevant to the functional requirements were defined and collected (as comprehensively as possible) for the selected alloys (Appendix C). Given the wide range of data sources consulted, it was recognized that questions regarding the reliability and consistency of the collected data were likely to arise. Therefore, general background knowledge of alloying principles and the relationships between alloy composition, structure and properties were reviewed and used to help evaluate the real potential of compositions for SOFC applications.

The selection criteria for the different categories of alloy compositions are discussed below. Selected properties relevant to the interconnect materials requirements are also reviewed and discussed below in terms of general alloy principles. The concepts of alloy design are also elaborated, in an attempt to provide guidance for the modification of currently available compositions and future development of new alloy compositions exhibiting improved materials performance as an interconnect in SOFC.

II. Selection of Alloy Compositions

As mentioned above, the obvious choice for the current collector material would be a high temperature alloy that provides oxidation resistance under the high temperature exposure conditions that characterize the SOFC environment. Nominally, high temperature alloys can be classified into Ni-, Fe- and Co-based superalloys, Cr-based alloys and stainless steels. All of these alloys typically contain Cr and Al, which provide oxidation resistance by forming thin, adherent protective layers of Cr_2O_3 and Al_2O_3, respectively. Because of the overall higher resistance of alumina scales, it appears that Al_2O_3 forming alloys may not be suitable to be used as interconnects, at least for some designs, because of the performance loss (voltage loss across the insulating alumina scale). Thus, it is necessary to establish "critical" minimum Cr contents and "critical" maximum Al contents needed for long-term protection. (It should be noted that alumina formers may find application in SOFC stack designs which can exclude the alumina scale from the current collection function within the stack).

1. Ni-, Fe-, and Co-Base Superalloys

"Superalloys," usually based on group VIIIA elements, have been developed for elevated temperature service where relatively severe mechanical stresses are encountered and high surface stability is required. These alloys are structurally characterized by the γ austenitic FCC matrix plus a variety of secondary phases. The principal secondary phases are the carbides MC, $M_{23}C_6$, M_6C and M_7C_3 (rare) in all Ni-, Fe-(Ni-) and Co-base alloys, and γ' FCC ordered $Ni_3(Al,Ti)$ intermetallic compound in only Ni- and Fe-(Ni)- base compositions.

In the following, a selection criterion, mainly consisting of the "critical" minimum Cr content and "critical" maximum Al content is established for Ni-, Fe-, and Co-base superalloys.

1) "Critical Minimum" of Cr%

(i) Ni- and Fe-Base Superalloys:

As suggested by Robb, Wasielewski, Giggins and Pettit [1,2], the "critical" minimum Cr content to ensure the formation of a protective, continuous Cr_2O_3 scale is approximately 20-25 wt% chromium. This "critical" amount of Cr is also required to prevent the rupture of the protective scale, and internal oxidation due to the depletion of chromium at the sub-surface. This suggested "critical" minimum is consistent with the work of Birks and Rickert [12], who concluded that the oxide scale consists primarily of Cr_2O_3 when the Cr content in the alloy is greater that 20%; spinel $(Cr,M)_3O_4$ phases tend to form when the Cr concentration is less than 10%. Furthermore, a Cr content of more than 20 wt% in Ni-, Fe-, and Co-base alloys has been recommended as the principal method for combating hot corrosion [3]. For Ni-base alloys, Sims et al. [4] concluded that at least 15 wt% Cr was needed for reasonable resistance to hot corrosion and that the optimum was 18-19 wt%.

It should also be noted that, in addition to Cr and Al, trace elements such as La, Ce, Y, etc., might also directly or indirectly contribute, sometimes significantly, to the oxidation and corrosion resistance. For Ni-base alloys with Cr contents less than 20%, an appropriate amount of Al is typically added to enhance the oxidation resistance.

Thus it appears that, for optimum oxidation and corrosion resistance, the Cr content in Ni- and Fe-base alloys should be more than ~18 wt%, which is therefore recommended as the "critical" minimum content for Ni- and Fe-base superalloys.

(ii) Co-Based Superalloys:

Experimental studies conducted by Kofstad and Hed [5-7] indicated that additions of 9% Cr decrease the already poor oxidation resistance of pure cobalt by a factor of three. The oxide scale is predominantly CoO, with some $CoCr_2O_4$. Upon further additions of Cr to 25%, the oxidation rate decreases to a minimum, and a protective scale of Cr_2O_3 is established. Sims et al. [4] mentioned an optimum content of 25-30% Cr in Co-base alloys for hot corrosion. It is also noted that oxidation and corrosion resistance of Co-base alloys could be further improved by additions of Al, B, Ca, and Zr. Therefore, the "critical" minimum content of Cr was set as 22% for Co-base alloys.

2) "Critical" Maximum of Al%

(i) Ni- and Fe-Base Superalloys:

Based on the ratio of Cr and Al, Wasielewski and Rapp[1] classified superalloys containing both Cr and Al into the following three categories:

a) A NiO scale with Cr_2O_3 and Al_2O_3 internal oxides for both low Cr and Al contents-type I;
b) An Cr_2O_3 scale with Al_2O_3 internal oxides for high Cr (>15%) but low Al (1%<Al%<3%)-type II;
c) An exclusive α-Al_2O_3 scale for relatively high Cr (>15%), and high Al (>3%)-type III.

The steady-state parabolic rate constants are decreased by more than one order of magnitude in passing from type I to type II, and again in passing from type II to type III. The elimination of NiO as the steady-state scale is accomplished when the combined volume fraction of Cr_2O_3 and Al_2O_3 precipitates is sufficient to block inward diffusion of oxygen into the alloy matrix. Thus the sidewise growth of Cr_2O_3 particles can develop a "protective" inner scale of Cr_2O_3. The presence of an inner layer drastically reduces the local oxygen activity at the metal-interface so that an enrichment of Al_2O_3 particles occurs. For type III alloys, which have sufficient bulk Al or volume fraction of alumina, an α-

Al_2O_3 layer forms beneath the Cr_2O_3 inner scale, which dramatically enhances the oxidation resistance, but acts as an electrical insulating layer.

Therefore, an Al content of 3 wt% was established here to be the "critical" maximum. It was found that in the original list (Appendix A), no Ni-base alloys with Cr content of higher that 18 wt% contain an Al content of higher than 3 wt%. For Fe-base alloys, application of this "critical" maximum only eliminates Incoloy MA956 with 4.5% Al, which is listed in the alumina forming alloys. Recent studies by Quadakkers et al [8] confirm that MA 956 is not suitable for typical SOFC interconnect applications due to the high electrical resistance of the formed alumina-scale.

(ii) Co-Base Superalloys:

Normally, conventional Co-base alloys do not contain Al and depend on α-Cr_2O_3 for protection.

Note that, due to formability considerations, the casting alloys are left out for consideration at this stage. Only wrought alloys are listed here. Besides Cr and Al, Si is another alloy element that can provide oxidation resistance (by forming an insulating SiO_2 layer.) No criterion was established in term of Si content, but its effect on oxidation should be considered for some listed compositions that contain a fairly large amount of Si.

2. Cr-Base Alloys

The Cr-base alloys crystallize in the body-centered-cubic (BCC) structure and thus are not considered as superalloys by most metallurgists. As aluminum is not included in these compositions, no criterion was established, and thus all the Cr-alloys in the original list were considered to be selected for property collection.

3. Stainless Steels

Stainless steel is a generic term covering a large group of alloys, which are commonly known for their oxidation resistance. In terms of their structures, stainless steels are usually divided into four groups: (i) ferritic steels; (ii) austenitic stainless steels; (iii) martensitic steels and (iv) precipitation-hardening steels. It is noted that some FCC austenitic stainless steels, usually with significant amount of Ni addition, are classified into superalloys and listed in Fe-Ni-base superalloy tables.

The ferritic stainless steels typically have 11 to 30% chromium as the major alloy addition and are low in carbon. These compositions are substantially ferritic, a body-centered-cubic (BCC) structure at all temperatures and therefore can not be strengthened by heat treatment, although some of the "ferritic" grades do undergo some austenite formation at high temperatures and can transform into martensite. Ductility and formability of ferritic compositions are less than that of the austenitic grades. Their corrosion resistance competes with the austenitic grades for certain applications. Ferritic stainless steels are magnetic, and resistance to high-temperature corrosion is better than that of martensitic types. They generally have good ductility and can be welded or fabricated without difficulty.

The aforementioned ferritic stainless steels also include pure or superferritic ones (refer to details in Part III, 5)), such as 29-4, E-Brite 26-1, etc., and ferritic/austenitic duplex structures, such as Carpenter 7-Mo, AL 255, etc. The ratio of ferrite (BCC) to austenite (FCC) in duplex structures mainly depend on the nickel content, which is typically in the range of 4.5 to 8%. This nickel content is not sufficient to generate a fully austenitic structure, thus resulting in a combination of BCC ferritic and FCC austenitic structures.

Recently, some ferritic stainless steels have specifically been developed for glass sealing applications, where a close TEC match in the whole temperature range is required. Due to oxidation resistance considerations, only those with chromium content higher than the minimum are listed in the table of ferritic stainless steels.

Austenitic steels with a FCC structure are characterized by larger linear thermal expansion coefficients, which are typically in $18 \sim 20\times10^{-6}$/K (RT~800^{o}C). For example, Project 70 Stainless and Carpenter 21Cr-6Ni-9Mn are common standard and non-standard austenitic stainless steels and have linear thermal expansion coefficients of 19.0×10^{-6}/K and 20.0×10^{-6}/K (RT~760^{o}C) [10], respectively. Thus all standard and non-standard austenitic compositions are unlikely to be satisfactory candidates for rigid seal stack designs.

Martensitic and precipitation-hardening steels, which typically contain a Cr content of less than 18%,[9] were not included in this study; their maximum service temperature without excessive scaling is usually less than 650^{o}C[11].

Therefore only ferritic standard and non-standard steels, including duplex structures, are evaluated using the same criterion in chemical composition as established for superalloys, i.e. the "critical" minimum Cr content is set at 18 wt% and the "critical" maximum Al content at 3 wt%.

4. Alumina Forming Alloys

It has long been known that the oxidation resistance of alloys with a fairly high amount of Al is orders of magnitude higher than an alloy only containing Cr. It might be possible to make use of these alloys in SOFC stacks by designing the components to exclude the insulating alumina scale from the current conduction path. In this case, a "minimum" Al content (with reference to the Cr content) should be established. By referring to the previously mentioned Wasielewski and Robb rule[1] for classification of superalloys, the following criteria were established to create an alumina forming alloy table:

i) High Cr (>18%) and high Al (>3%)- type I;

ii) High Cr (>18%) and fairly high Al (1<Al%<3%) – type II;

iii) Fairly high Cr % (15~18%) and high Al (>3%) - type III.

It is expected that both type I and III will form continuous Al_2O_3 inner layers. For type II, the Al content may not be enough to form a continuous Al_2O_3 layer, but might be a major component in the oxide scale to improve the oxidation resistance. In this work, alloys with Cr%≥15 and Al%≥3 are defined as alumina formers and separated into the Table of Alumina Forming Alloys.

III. Alloy Properties Relevant to the SOFC Interconnect Application

According to the materials functional requirements for a metallic interconnect in SOFCs, the following parameters or properties must be used to evaluate alloys: (i) thermal expansion coefficient; (ii) electrical conductivity of both bulk matrix and scale; (iii) oxidation resistance; (iv) corrosion resistance; (v) yield strength; (vii) elastic modulus; (viii) formability or tensile elongation; (ix) cost; (x) other properties, such as hydrogen embrittlement resistance, machinability, and etc. For this study, it was expected that it would not be possible to obtain all data required. Also, some data might not be reliable, particularly if considerable scatter existed in data taken from different sources. In those cases, knowledge of alloying principles can be used as a tool to approximate the unavailable data and to evaluate the reliability and consistency of collected data. In the following, the parameters or properties corresponding to the materials functional requirements will be reviewed and discussed in terms of general alloying principles.

1) Thermal expansion coefficient (TEC)

When available, the average linear TEC over the temperature range of RT-800^{o}C has been collected from the available literature data for a large number of Ni, Fe, Co and Cr base alloys. The TEC of alloy systems largely depend on the crystal lattice structure. In term of matrix crystal structure, high temperature alloys can also be classified into BCC ferritic and FCC austenitic formers, as shown schematically in Figure 1. Ni-, Fe-, Co-base superalloys and austenitic stainless steels are FCC formers; ferritic stainless steels as well as Cr-base alloys are BCC formers. As a rule of thumb, BCC formers have a lower TEC than FCC formers. For example, the TEC of pure ferritic stainless steels are typically in the range of $12.0\sim13.0\times10^{-6}$ K^{-1} from RT to 800^{o}C, therefore having a better thermal expansion match to typical SOFC components. If the concentrations of substitutional elements are increased beyond the phase stability region, austenite may be formed in the ferritic matrix, resulting in a duplex structure. All duplex stainless compositions have shown higher TEC than their pure ferritic counterparts. Fully austenitic alloys with FCC structure possess higher thermal expansion coefficients than BCC formers. Austenite stainless steels and Fe-base superalloys usually have a TEC in the range of $15.0\sim20.0\times10^{-6}$ K^{-1} from RT-800^{o}C. Ni-base superalloys, also with FCC structure, tend to have TEC in the range of $14.0\sim19.0\times10^{-6}.K^{-1}$from RT to 800^{o}C. Co-base superalloy compositions normally possess a TEC of $14.0\sim17.0\times10^{-6}$ K^{-1} from RT to 800^{o}C.

The TEC data of different groups of alloys, along with other properties, is outlined in Table I.

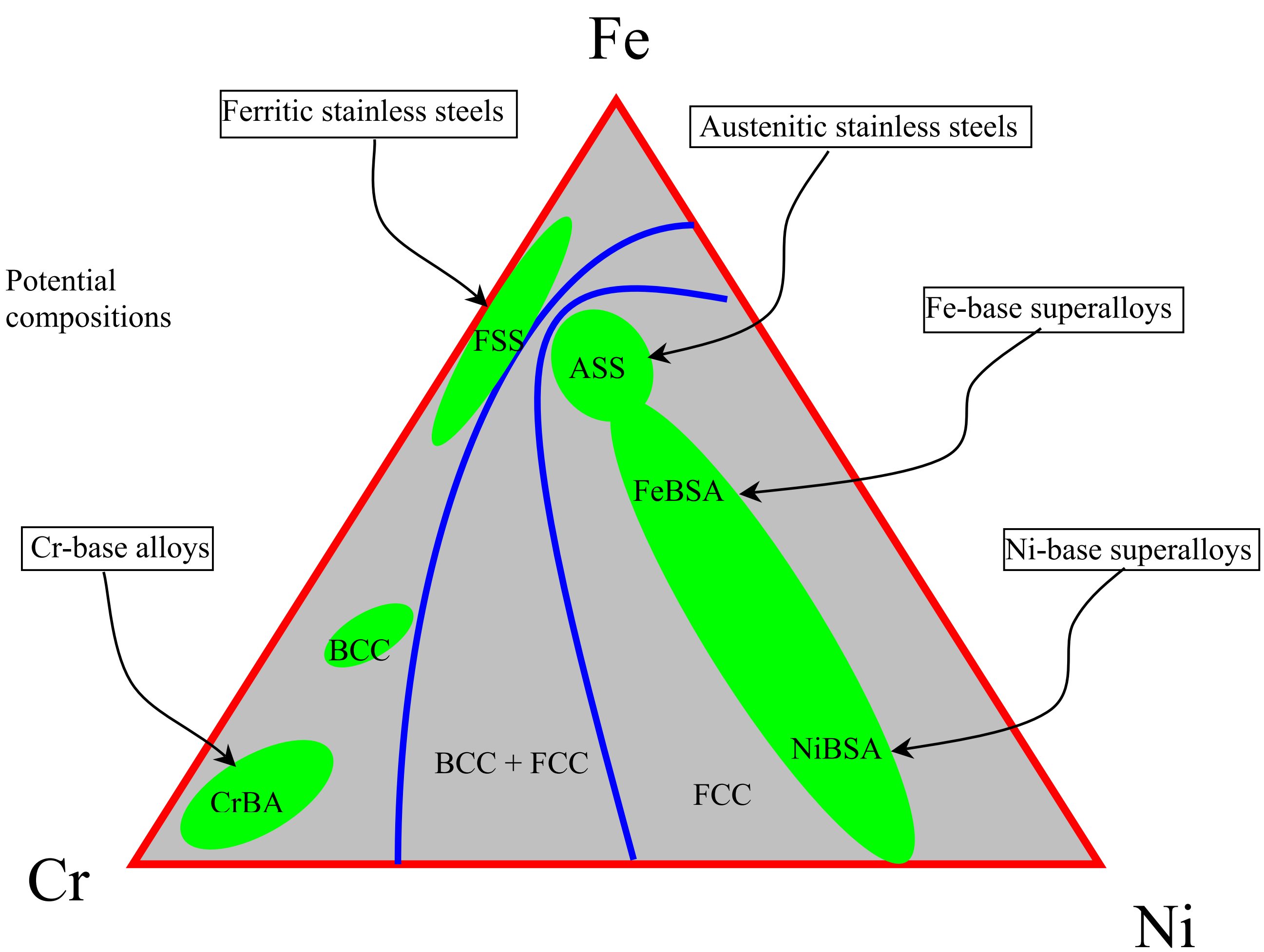


Figure 1. Schematic of alloy design for SOFC applications.

Table I. Comparison of key properties of different alloy groups for SOFC applications

Alloys	Matrix structure	TEC $\times 10^{-6}.K^{-1}$	Oxidation resistance	Mechanical strengths	Manufactur-ability	Cost
CrBA	BCC	11.0-12.5 (RT-800^{o}C)	Good	High	Difficult	Very expensive
FSS	BCC	11.5-14.0 (RT-800^{o}C)	Good	Low	Fairly readily	Cheap
ASS	FCC	18.0-20.0 (RT-800^{o}C)	Good	Fairly high	Readily	Cheap
FeBSA	FCC	15.0-20.0 (RT-800^{o}C)	Good	High	Readily	Fairly expensive
NiBSA	FCC	14.0-19.0 (RT-800^{o}C)	Good	High	Readily	Expensive

2) Electrical conductivity

For high temperature alloys, the electrical resistance increases with increasing temperature and is the sum of two parts, bulk resistance and scale resistance. The bulk electrical resistance, which usually can be easily found in handbooks and electronic sources, is collected and listed in Appendix C; typical values are 60-130×10^{-6} Ω.cm at RT with only slight increases with temperature.

In the long term, the electrical resistance of the scale usually dominates the electrical behavior of high temperature alloys during SOFC operation. As mentioned earlier, the scale could be either Cr_2O_3 or Al_2O_3. Cr_2O_3 is an electronic conductor, which at 900°C has a conductivity of 10^{-2}~10^{-1} $S.cm^{-1}$ [16].

The temperature dependence of the conductivity can be expressed by:

$$\sigma = \sigma_o \exp(-E_a/RT)$$

where σ = conductivity (= 1/ρ, where ρ = resistivity), E_a is the activation energy, R is the gas constant, and T is absolute temperature. σ_o and E_a were reported by Kofstad et al. [15~17] at 0.04-0.06 S/cm and E_a=180 KJ/mol, respectively, in a temperature range of 800-1,000°C. Though the literature values of the electrical conductivity of alumina (α-Al_2O_3) show large discrepancies and vary by many orders of magnitude [16], it is universally acknowledged to be an electrical insulator. Kofstad and Bredesen [21] concluded that the electrical conductivity of alumina is lower than that of chromia by a factor of 10^5-10^6. Accordingly, chromia formers rather than alumina formers should be considered as interconnect materials, unless the SOFC stack design excludes the Al_2O_3 scale from the electrical path.

In principle, the area specific resistance (ASR) can be evaluated according to Cr_2O_3 scale thickness, which is a function of the rate constant, temperature and time, assuming the scale growth follows the parabolic law. This ASR estimation however yields a lower value than those reported in most recent studies [14,18~20, 22]. Almost all of these studies concluded that the Cr_2O_3 scale growth and thus the electrical resistance would reach an unacceptable level in the long term under the SOFC operating conditions. It is believed that the discrepancy is caused by the complexity of Cr_2O_3 scale growth, which will be described in the next section. The growth of Cr_2O_3 scales on high temperature alloys in practical environments is much more complicated than the growth on pure chromium, which is generally used in lab-studies to obtain the rate constant.

Overall, it appears that, in the long term, the bulk and/or surface compositions of high temperature resistant alloys must be engineered to decrease the oxide scale growth rate and/or modify the scale chemistry so that the resistance of the scale can be limited to acceptable levels (refer to details in Part IV).

3) Oxidation resistance

In Wagner's theory of oxidation [23, 24], it is assumed that during the oxide growth, the transport of oxygen ions and/or metallic cations through the oxide scale takes place by lattice diffusion. Thus the growth of the surface oxide scale follows the well-known parabolic law:

$$X^2 = kt + X_o^2$$

where X and X_0 is the thickness of the scale at time t and t=0, respectively; k is rate constant. It has been experimentally shown that the parabolic law of the growth of scale is valid for essentially all cases in which the scale is adequately thick and homogeneous. It has been noted that[13] the net current flow in SOFCs may cause some deviation from the parabolic law prediction.

Recent studies conducted on SOFC-related oxidation of high temperature alloys indicate that in most cases the oxidation of high temperature alloys still obeys the parabolic law under current flows appropriate for SOFC [14]. Hence, in this study, the parabolic rate constant is selected as the parameter measuring the oxidation resistance of high temperature alloys. Our literature survey indicates that data collected from textbooks, handbooks, and electronic data sources exhibit considerable scatter.

In spite of the lack of consistent and complete data, the oxidation resistance can still be qualitatively understood in regard to alloy chemical composition. As stated previously, Cr and Al (and Si) are the major oxide scale formers to provide oxidation resistance in the high temperature alloys. The growth rate constant of Al containing alloys can be orders of magnitude lower that that of Cr containing alloys. Thus alumina formers typically have much higher oxidation resistance than alloys containing only chromium to provide protection. Besides, it is also common for the alumina formers to possess a stronger adherence between the scale and bulk matrix than chromia formers, and thus they demonstrate better scaling resistance against oxide spallation and cracking under thermal cycling.

Weak bonding of chromia scales with the underlying substrate is dictated by the following growth features [15]:

(i) The scales grow predominantly by outward chromium diffusion along grain boundaries in the chromia scale. But, there is also some inward oxygen diffusion to result in formation of oxide within the scale, which can cause growth stress in the scale.
(ii) As the result of growth stress and the growth mechanism, the scales are often convoluted and contain cavities and porosity; furthermore, the scales often detach locally from the metal substrate
(iii) Chromia scales may also exhibit extensive cracking at high temperatures and may also spall on cooling and thermal cycling.

The use of so called "reactive elements," such as Ce, La and Y, or their oxide forms, has been found to greatly modify this growth behavior, which will be discussed in detail in Part IV. As a result, alloys with additions of reactive elements typically possess much improved oxidation, electrical and scaling resistance.

4) Corrosion resistance

The SOFC operates at high temperature (700-1,000^oC) with fuel (such as H_2 or reformed natural gas) on the anode side and air on the cathode side. Moisture could be present on both the cathode and anode sides, and, therefore, in contact with the metallic interconnects. Sulfur impurities present in the fuel gas stream are also expected to exist, although upstream desulfurization has been commonly applied to decrease the sulfur impurity level to sub ppm or ppb levels. Thus, besides oxidation, the interconnect could also suffer from sulfidation, hot corrosion (in the presence of molten salt), and carburization, etc. Thermal stresses generated in the SOFC stack due to large temperature gradients across the current collector could also accelerate the corrosion process due to premature cracking and spallation of the oxide scale. The presence of complex gaseous species in the fuel environment also result in the establishment of grain boundary corrosion, internal oxidation and localized metal loss resulting in overall reduction of component life. Sulfidation refers to an aggressive attack resulting from the combined effects of oxidation plus reactions with sulfur, which may be present in the fuel gas stream. Our literature search indicated that no standardized data is available for quantitative comparison. Thus only qualitative classification is currently possible within the scope of this report. Generally, the degree of sulfidation or hot corrosion can be related to the chromium content and alloy chemistry in Ni-, Fe- and Co-base alloys. The effect of alloy elements on hot corrosion resistance is also discussed in the "Effects of Alloying Elements" section below.

5) Yield strength

The metallic interconnect is also required to have enough strength to help maintain the structural integrity of the stack during SOFC operation at high temperatures and under thermal cycling. Accordingly, the high temperature alloys for an interconnect should possess thermal fatigue resistance against possible structural fracture during thermal cycling, creep resistance to maintain the dimensional stability at high operating temperature, and rupture resistance to endure peak thermal stresses generated during SOFC operation. All the aforementioned strengths can be more or less correlated to the yield strength, σ_{yield}. For stainless steels, the compositions with higher yield strength usually possess higher creep and fatigue strengths, so do superalloys. The high temperature mechanical properties of some superalloys and stainless steel compositions are collected in Table II.

Thus the yield strength, which is also easily available, was used to represent mechanical strength of the alloys. Since most alloys except annealed low carbon steels do not have obvious yielding strains, the stress at 0.2% is defined as the yield strength, $\sigma_{0.2}$. When possible, the yield strength from bar tests at both RT and a high temperature (preferable around 800ºC) was collected. If bar test data was not available, sheet test data was used.

The yield strength of an alloy is a function of alloy composition, phase constitution and structure/microstructure. The alloy can be strengthened through combinations of the following mechanisms:

(i) Solution strengthening;
(ii) Precipitation hardening;
(iii) Martensitic hardening;
(iv) Carbide or added oxide strengthening;
(v) Work hardening.

Different alloy groups could have different combinations of strengthening mechanisms. For example, strengthening mechanisms for ferritic stainless steels are limited to work hardening and solution strengthening, in order to maintain their BCC ferritic structure. Precipitation hardening may also be applicable, but may not be useful in improving the strength of an alloy at elevated temperatures (e.g., 800ºC).

Overall, the superalloys and Cr-base alloys tend to have higher yield strengths than stainless steels; austenitic stainless and martensitic steels have higher yield strengths than ferritic stainless steels. The conventional ferritic stainless steels such as 430, 446, and 453 usually have a yield strength of about 300 MPa at RT. The yield strength of these stainless steels, however, drops quickly as the temperature increases over 700°C and usually ends up a number less than 50 MPa at 800°C. Consequently, these stainless compositions are typically characterized by substantially low creep and fatigue strength, which may be of concern for SOFC applications, especially in the long term.

In past years, numerous stainless alloy compositions have been developed for improved strength by increasing Cr content and adding other alloy elements, such as Mo. In order to maintain their ferritic structure, the interstitial elements of C and N are controlled at a very low level (usually <0.015%) by using novel refining process such as argon-oxygen decarburization (AOD) or vacuum melting. These structures with improved properties are called superferritic stainless steels. For instance, the AL 29-4 series, which are characterized by a high content of chromium, addition of molybdenum, and limited concentration of interstitial elements C and N through AOD refining, possess a yield strength almost twice of that of conventional ferritic stainless steels.

Table II. High temperature mechanical properties of superalloy and stainless steels

Alloys	Elastic modulus (GPa)	Yield strength $\sigma_{0.2}$ (MPa)	Creep strength σ_{ε}^{T} (MPa)	Rupture strength σ_{t}^{T} (MPa)
Superalloys				
Carpenter 19-9DL		138 at 815°C	$\sigma_{1\times10^{-5}}^{732^o C}$ =36	$\sigma_{1\times10^{3}}^{816^o C}$ =59
Incoloy 556™	148 at 800°C	220 at 760°C	$\sigma_{1\times10^{-5}}^{760^o C}$ =59	
Aktiebolag 253 MA	115 at 760°C	110 at 750°C	$\sigma_{1\times10^{-5}}^{760^o C}$ =29	
Haynes R-41	169 at 800°C	752 at 760°	$\sigma_{1\times10^{-3}}^{732^o C}$ =234	$\sigma_{1\times10^{3}}^{816^o C}$ =165
Inconel 625	160 at 760°C	421 at 760°	$\sigma_{1\times10^{-3}}^{760^o C}$ =234	$\sigma_{1\times10^{3}}^{816^o C}$ =96
Pyromet 680	144 at 816°C	241 at 760°	$\sigma_{1\times10^{-5}}^{732^o C}$ =55	$\sigma_{1\times10^{3}}^{816^o C}$ =62
Stainless steels				
AL 446	200 at RT	275* at RT 55* at 760°C	$\sigma_{1\times10^{-5}}^{760^o C}$ =7.6	$\sigma_{1\times10^{3}}^{760^o C}$ =13.5
Carpenter 443	200 at RT	345 at RT 41 at 760°C	$\sigma_{1\times10^{-4}}^{704^o C}$ =7.0	
AL 439 HP™	200 at RT	310 at RT 48 at 760°C		$\sigma_{1\times10^{3}}^{816^o C}$ =7.0
AL 441 HP™	200 at RT	290 at RT 58 at 760°C		$\sigma_{1\times10^{3}}^{816^o C}$ =11.0

* Minimum as required.

6) Elastic modulus

The elastic modulus at RT and high temperature was collected and listed for most of the alloy compositions. Typically the superalloys have an elastic modulus in the vicinity of 200 GPa, although the moduli of specific polycrystalline alloys can vary from 170~240 GPa at room temperature depending on the alloy systems. Ferritic stainless steels also have moduli around 200 GPa. The elastic modulus decreases at high temperatures.

7) Joinability

No standard parameter and data are available to quantitatively measure the joinability of various metals or metals and ceramics of interest. Overall, alloys with a FCC matrix structure, such as superalloys, have better joinability than those with a BCC matrix, such as Cr-base alloys. Ni- and Fe-Ni-base superalloys are considerably less weldable that the Co-based superalloys. Austenitic stainless steels have better joinability than ferritic stainless steels, which may be exhibit the following difficulties:

(i) Excessive grain growth at high temperature;
(ii) Sensitization when the steel is cooled from temperatures above 925°C;
(iii) Lack of ductility.

8) Formability

Conventionally, the Erichsen or Olsen cupping depth (mm) is used to measure the formability. If the E or O cupping depth at room temperature (RT) was not available, the elongation data from bar tests, which is available from many sources, is collected as an alternative for evaluation. Generally, alloys with higher elongation rate are expected to have better formability. Overall, superalloys and stainless steels are better than Cr-base alloys.

9) Cost

The price of stainless steel 446 (in ¼" mils sheet) is used as the basis. The cost factor is defined as the ratio of the price of a specified alloy to that of 446. Superalloys are more expensive than stainless steels and among various superalloys, Co-base alloys are more expensive than Ni-base; Ni-base alloys are more expensive than Fe-base. Mechanically alloyed compositions are more expensive than their conventional counterparts.

10) Others, including resistance to hydrogen embrittlement, and machinability.

BCC matrix alloys are typically more sensitive to hydrogen-induced embrittlement than FCC matrix alloys.

Machinability of alloys is expressed as a percentage by referring to Seco Tools AB. Decreasing values indicate increasing machining difficulty.

The machining ability of stainless steels can be summarized as the followings:

(i) The martensitic stainless steels are usually machined in the annealed conditions. Their machinability is generally intermediate to the ferritic and austenitic grades;
(ii) The ferritic grades are easiest to machine;
(iii) The austenitic grades are gummy and give the most difficulty;
(iv) Improved machinability (in all cases) can be obtained through addition of lead, sulfur, or phosphorus.

IV. Effects of Alloy Elements

Alloy properties are determined by alloying compositions, phase constitution, and structure. Alloying elements and their quantity are the most important factors to be considered in the alloy design for the desired structure and thus the required properties.

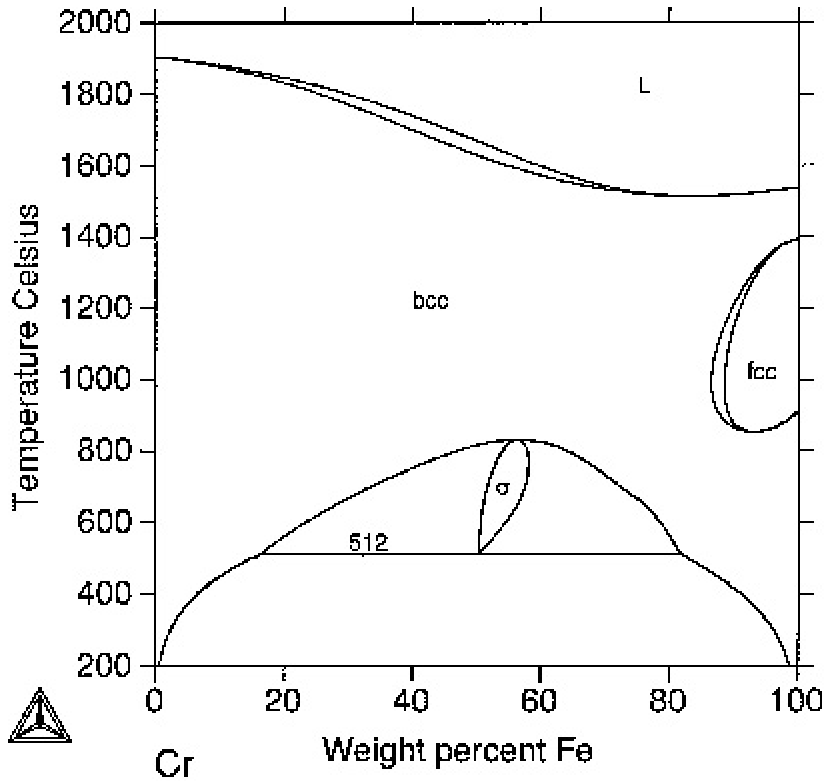
Cr, Ni and Fe are three major alloy elements in high temperature alloys. As shown in Figure 1, the quantities of these three elements in an alloy could decide the phase constitution, structure and thus properties.

As mentioned previously, Cr is a primary element for forming oxide scales for providing surface stability of high temperature alloys. To have enough oxidation and corrosion resistance at the SOFC operating temperatures, ideally the amount of Cr in most high temperature alloys should not be less than a number around 18%, as described previously. In addition, Cr is also an important element for improving mechanical properties through solid solution strengthening and carbide hardening by forming Cr_7C_3 and $Cr_{23}C_6$. In Fe-base high temperature alloys, including superalloys and stainless steels, Cr, by producing the gamma loop in Fe-Cr phase diagram (Figure 2), can be utilized to stabilize ferrites and destabilize austenite. For the pure Fe-Cr system, a minimum of 13 wt% Cr is required to maintain the BCC ferritic structure from RT to the melting point. For martensitic stainless steels, the Cr content cannot be too high, normally less than 18%, in order to generate austenite at high temperatures, which transforms to martensite during subsequent cooling. In Cr-base alloys, a BCC crystal structure is maintained which contributes to thermal expansion matching with other SOFC components.

Though the addition of more Cr increases the oxidation resistance and also helps stabilize the BCC ferritic structure for a TEC match, increased Cr concentration could also lead to some disadvantages for SOFC applications. As shown in the Fe-Cr phase diagram in Figure 2, a second phase, called the sigma phase, can precipitate along grain boundaries in the alloy matrix at a temperature in the range of 550~870^{o}C when the concentration of Cr is higher than 14~15 wt% [11]. The formation of sigma phase along grain boundaries not only causes a lower ductility (sigma phase embrittlement), but also results in deteriorated oxidation resistance as well as thermal expansion mismatch in SOFC, as indicated in our recent studies[25]. It is also reported that increasing Cr contents in ferritic structures decrease the thermal expansion coefficient of alloy compositions, but also creates "knees" in the thermal expansion curves if the Cr concentration becomes too high [26].

As indicated by many studies [14,18~20, 22], the resistance of the chromia scale will reach an unacceptable level after hundreds of hours under current SOFC operating conditions. Accordingly, it appears that the high temperature alloys have to be modified so as to inhibit the growth of the chromia scale and decrease the resistance of the scale. One effective approach is to change the bulk or surface chemistry by adding reactive elements, such as Y, Ce, or La (or their oxide forms). These elements, when added as a trace amount (0~0.1%) to the alloys, significantly modify the growth behavior of the chromia scale, as listed by Kofstad [15] in the following:

(i) The preferential formation of chromia scales is enhanced;
(ii) The growth rate of chromia scales is reduced;
(iii) The adherence of chromia scales to the alloy substrate is improved;
(iv) The scales are denser.



Cr-Fe Crystal Structure Data

Phase	Pearson Symbol	Struktur Bericht	Prototype	Model
bcc	cI2	A2	W	RK
σ	tP30	$D8_b$	σ-CrFe	CE
fcc	cF4	A1	Cu	RK

Figure 2. Cr-Fe phase diagram and crystal structure data.
(After J.O. Anderson and B. Sundman [27])

As a result, theses reactive trace elements significantly increase the oxidation resistance of alloys, decrease electrical resistance of the scale, and improve the scaling resistance under thermal cycling.

Another approach to inhibit the growth of the chromia scale is to modify the surface of currently available compositions by applying a dense coating, whose composition is usually a conductive oxide, acting as a diffusion barrier to decrease the growth of chromia layer. The coatings are also expected to decrease or prevent the evaporation of chromia scale [32,33]. Vaporized chromium species can deposit at the interface of the cathode and electrolyte, resulting in higher polarization by decreasing the active sites at the interface [34]. Ideally, the conductive oxide used for the coating should be an electronic conductor with very low ionic conductivity ion order to decrease cationic and anionic transport through the coating layer. Coatings with perovskite oxides traditionally used in SOFC have demonstrated promising results in improving the surface stability of chromia forming alloys [22, 28-31].

Besides Cr, Al and Si are the other two elements that can be used to provide oxidation resistance. It has been demonstrated that Al is much more effective than Cr in improving oxidation, corrosion and scaling resistance by forming an Al_2O_3 layer on the high temperature alloys. The alumina formed on the alloy surface is also thermodynamically stable and thus does not exhibit the poisoning effects associated with the evaporation of species from the chromia scale. The insulating nature of the alumina scale, however, may prevent any application of alumina formers in the active electrochemical area of the cell. Due to the lack of adherence and susceptibility to internal oxidation, Si is not commonly used in alloying to provide oxidation resistance. It is also postulated that the silica based or silica containing scale could become very insulating in the active cell region resulting in performance loss.

Ni acts to stabilize the austenite structure and form ordered γ'precipitation for strengthening of Ni- and Fe-base superalloys. Thus in the ferritic structures, the Ni amount must be controlled at a lower level (typically less than about 2~3.0% for ferritic stainless steels, but dependent on content of Cr, C, N, etc.) in order to maintain their BCC crystal structure even at high temperatures. With increases in the amount of Ni, the alloy matrix will transform from BCC to FCC. The thermal expansion coefficients of FCC alloys might be too high for consideration for SOFC applications (at least for stacks utilizing rigid, bonded seals (e.g., glass, glass-ceramic seals)).

Fe is the base element for the stainless steels and Fe-base superalloys. Below 912^{o}C, pure Fe has a BCC ferritic structure and transforms to FCC austenitic structure after this point. As discussed earlier, Cr helps to stabilize the BCC ferritic structure. By the contrast, Ni, Mn, Mo, Co and many other substitutional elements help stabilize the FCC austenitic structure by pushing the gamma loop in the Cr-rich direction. Another important function of Fe is to form Fe_3C in steels and also act as a solid solution strengthener.

Mo, W, Ti, Nb and Ta are carbide formers and usually used to improve mechanical strength.

Interstitial elements of C and N can also play important role in alloy design. Both elements can be used to strengthening alloy matrix through interstitial solution hardening mechanism and also helps formation of austenites by moving the gamma loop to the Cr rich direction. So, in the ferritic structure, the content of these interstitial elements should be controlled at a limited level.

Some trace elements, such as phosphorus and sulfur, typically have detrimental effects on alloy properties, but could modify manufacturability. Their quantity is usually closely controlled in most compositions.

The effects of alloy elements are summarized in Table III.

Table III. Effects of alloying elements on properties relevant to SOFC applications

Alloying Elements	Composition range				Effects on properties relevant to SOFC applications
	Ni/Fe-BSA	CoBSA	SS	CrBSA	
Base-elements					These elements are the base elements for high temperature alloys. Besides they are used for strengthening and/or improving mechanical strength.
Ni	Base For NiBSA	0-22	0-20		Base element for NiBSA; Stabilizes FCC austenite and increase TEC; Be less that 2.0 for BCC ferritic structures with lower TEC; Form hardening precipitates to increase mechanical strength for Ni-/Fe-BSA.
Fe	Base For FeBSA	0-20	Base	0-5.0	Base element for FeBSA and SS, usually cheaper than Ni, Co- and Cr-bases; Improve mechanical strength through solid solution strengthening and carbide (Fe_3C) formation.
Co	0-20	Base			Base element for Co-base alloys, expensive; Raises solvus temperature to affect amount of precipitates; Improve mechanical strength w/ solid solution strengthening;
Cr	5-25	19-30	5-28	Base	Base element for BCC Cr-base alloys, expensive and difficult in manufacturing; Improve oxidation/corrosion resistance, and mechanical strength through M_7C_3,$M_{23}C_6$ formation and solid solution strengthening.
Carbide formers or strengthening elements					The major function of these elements is to improve mechanical strength of base alloys through carbide formation. Besides these elements are usually sitting on substitutional positions for solution strengthening.
Mo	0-12	0-11	0-12	0-10	Increase mechanical strength through carbides (MC, $M_{23}C_6$, M_6C) formation and solid solution strengthening; Improve pitting corrosion resistance.
W	0-12	0-11	0-12	0-10	Increase mechanical strength through carbides (MC, $M_{23}C_6$, M_6C) formation and solid solution strengthening.
Ti	0-6.0	0-4.0	0-6.0	0-0.5	Improve mechanical strength through formation of carbide (MC) and precipitates γ' $Ni_3(Al,Ti)$.
Nb	0-5.0	0-4.0	0-6.0		Improve mechanical strength through carbide (MC) formation; precipitation strengthening and solution hardening.
Nb,Ta	0-12.0	0-9.0	0-12.0		Improve mechanical strength through carbides (MC) formation and solution hardening; Modify oxidation resistance.
Interstitial elements					These elements are sitting on interstitial positions in the lattice of matrix, and may form carbides on grain boundaries. They are austenite stabilizer and thus ought to be controlled to limited level in ferritic structure.
C	<0.20 Ni-B <0.78 Fe-B	0-1.0	<0.02 FSS <0.78 ASS		Improve mechanical strength through carbide (Fe_3C, M_7C_3, M(CN)) formation and solution strengthening; Causes grain boundary segregation by forming carbides. Austenite former and closely controlled in ferritic structures.
N			<1.00		Improve mechanical strength through formation of M(C,N) carbonitrides and solution strengthening; Austenite stabilizer and closely controlled in ferritic structures for lower TEC.

Continue Table III.

Alloying Elements	Composition range				Effects on properties relevant to SOFC applications
	Ni/Fe-BSA	CoBSA	SS	CrBSA	
Scale formers					The major function of these elements is to form a oxide scale on the alloy surface to protect surface.
Cr	5-25	19-30	5-28	Base	Form semiconductive Cr_2O_3 scale to provide oxidation and corrosion resistance; For optimum performance, the Cr content should not be less than 18% in Ni-/FeSA and SS; Increase mechanical strength through M_7C_3,$M_{23}C_6$ formation and solid solution strengthening.
Al	0-6.0	0-4.5	0-6.0		Form an insulate Al_2O_3 scale to give a much better oxidation Cr_2O_3 scale; For continuous and adherent scale, Al should be over 3%, but usually less than 5%; Form precipitates γ' $Ni_3(Al,Ti)$ for hardening.
Si	0-5.0	0-6.0	0-2.0	0-2.0	Form an insulate SiO_2 scale for oxidation resistance; Adherence of the scale is weaker than Cr_2O_3 and Al_2O_3 scales; Be susceptible to internal oxidation.
Reactive elements					The so-called reactive elements, usually rare earth elements plus Y, can dramatically improve oxidation, corrosion, and scaling resistance. Besides their oxide forms can also help improve high temperature mechanical strength.
Re	0-0.200	0-0.200	0-0.200	0-0.200	Dramatically improve oxidation and hot corrosion resistance; Decrease resistance loss at the interface.
Re_2O_3	0-2.0	0-2.0	0-3.0	0-2.0	Increase oxidation resistance significantly; Improve mechanical strength through oxide dispersion. Raise price if mechanical alloying is used to disperse oxides.
Others					
Mn	<1.0 for NiBSA 0~5.0 for FeBSA	0-2.0	0-6.0	0-2.0	Used to replace Ni and thus cut the price, typically 2 Mn for 1 Ni.
P					Usually be considered detrimental and closely controlled; But promote general precipitation of carbides in Fe-base alloys and improve machinability.
S					Usually be considered detrimental and closely controlled; But promote machinability.

Re: rare earth elements, such as Y, La, Ce.
NiBSA: nickel based superalloy; FeBSA: iron based superalloy; CoBSA: co-base superalloys.
CrBA: Cr-base alloys.
SS: stainless steels; FSS: ferritic stainless steels; ASS: austenitic stainless steels.

V. **Conclusions**

Alloys showing high temperature oxidation resistance can be considered as potential interconnection / bipolar separator materials for SOFC application. The high temperature alloys of interest include Ni-, Fe-, Co-base superalloys, Cr-base alloys and stainless steels. The oxidation and corrosion resistance of selected alloy systems can be improved through the addition of alloying elements, such as Cr and Al, which can form an adherent scale on the alloy surface to provide the necessary protection of the metallic substrate and long term structural stability of the component. To form a continuous and adherent scale for long term oxidation and corrosion resistance, the Cr concentration in a high temperature alloy should not be less than about 18% in Ni- and Fe-base alloys (including stainless steels), and 22% for Co-base alloys. If an appropriate amount of Al (1~3.0 wt%) is added, the recommended minimum Cr content could be lower, but still must exceed about 15% in order to have enough internal oxidation resistance. As the Al concentration increases over 3% (but usually less than 5%), a continuous and adherent alumina layer will become the dominant component in the scale on the alloy surface. These alloys are classified as alumina formers, which demonstrate much more improved oxidation and scaling resistance than chromium formers. The insulating nature of the alumina scale may however prevent any application in SOFC, unless the stack is designed in such a way that the insulating alumina scale can be excluded from the electrical path.

In terms of TEC, ferritic stainless and Cr-base alloys offer better TEC match with other SOFC components than Ni-, Fe-, and Co-base superalloys and austenitic stainless steels. The high price and difficulty in fabrication of Cr- and Co-base alloys make them less favorable for intricate shape formation and large volume commercial application in SOFC power generation systems. Among the high temperature alloys, the stainless steels offer the lowest cost and reasonable manufacturability. A disadvantage of the ferritic stainless steels however is their lower mechanical strength, especially at the high temperatures required for operation of SOFC. Addition of more Cr and other alloying elements could lead to improved strength and corrosion resistance, but could also cause the sigma phase formation at the SOFC operating temperature around 800^{o}C, resulting in embrittlement and possible TEC mismatch.

Though numerous alloy compositions are available for consideration, there are few if any compositions which will satisfy the functional requirements of the interconnect in SOFC. One of the biggest concern remains that the currently available alloys may not offer high enough oxidation resistance and electronic conductivity of the oxide scale.

As a result, it is likely that new alloy compositions and/or protective surface modifications or coatings will be required. To improve the oxidation resistance and control the electrical resistance of the oxide scale at an acceptable level in the long run, one effective approach may be to add reactive elements, such as Y, Ce, La or their oxide forms into the high temperature alloys. These elements can be added as a trace amount (0~0.1%) to the alloys, but significantly modify the growth behavior and consequently improve oxidation and scaling resistance, as well as the scale resistance. Another possible solution is to apply a dense, electrically conductive coating to inhibit the growth of chromia scale and decrease the resistance of the scale. Considerable development work will be required in order to produce a completely satisfactory interconnect material for SOFCs operating at intermediate temperatures.

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Appendix A

Compositions of High Temperature Alloys

Ni-Cr or Ni-Cr-Fe Base Alloys

Alloys[a]	Nominal composition, wt%														UNS
	Ni	Cr	Fe	Co	C	Mn	Si	Mo	W	Cb	Ti	Al	B	Zr	Others	
AF2-IDA	Bal	12.0	0.5[b]	10.0	0.35	0.1[b]	0.1[b]	3.0[b]	6.0	--	3.0	4.6	0.015	0.10	1.5Ta	
Alloy 713C[c]	Bal	12.5	--	--	0.12	--	--	4.2	--	2.0	0.8	6.1	0.012	0.10	--	
Alloy 713LC[c]	Bal	12.00	--	--	0.05	--	--	4.5	--	2.0	0.6	5.9	0.01	0.10	--	
Astroloy[d]	Bal	15.0	--	15	0.06	--	--	525	--	--	3.5	4.4	0.03	--	--	**N13017**
B-1910	Bal	10.0	--	10.0	0.10	--	--	3.0	--	--	1.0	6.0	0.015	0.1	7.0Ta	
GMR-235[c]	Bal	15.5	10	--	0.15	0.25[b]	0.60[b]	5.25	--	--	2.0	3.0	0.06	--	--	
GMR-235D[c]	Bal	15.5	4.5	--	0.15	0.10[b]	0.30[b]	5.0	--	--	2.5	3.5	0.05	--	--	
Hastelloy C	56.0	16.5	6.0	--	0.15[b]	--	--	17.0	4.5	--	--	--	--	--	--	**N10002**
Hastelloy C-4	Bal	16.0	3.0[b]	2.0[b]	0.015[b]	1.0[b]	0.08[b]	15.5	--	--	--	--	--	--	--	**N06455**
Hastelloy C-22	51.6	21.5	5.5	2.5	0.01	1.0	0.1	13.5	4.0	--	--	--	--	--	0.3V	**N06022**
Hastelloy C-276	Bal	15.5	5.0	2.5[b]	0.02[b]	1.0[b]	0.08[b]	16.0	4.0	--	--	--	--	--	0.35V[b]	**N10276**
Hastelloy C-2000	Bal	23	--	--	0.01[b]	--	0.08[b]	16.0	--	--	--	--	--	--	1.6 Cu	
Hastelloy D-205 ™	Bal	20	6.0	--	0.03[b]	--	5.0	2.5	--	--	--	--	--	--	2.0Cu	

Alloys[a]	Nominal composition, wt%															UNS
	Ni	Cr	Fe	Co	C	Mn	Si	Mo	W	Cb	Ti	Al	B	Zr	Others	
Hastelloy G	Bal	22.0	19.5	2.5[b]	0.05[b]	1.5	1.0[b]	6.5	1.0[b]	--	0.7[b]	--	--	--	2.0Cu, 2.0Cb+Ta	**N06007**
Hastelloy G-3	Bal	22.0	19.5	5.0[b]	0.015[b]	0.80	0.40	7.0	1.5[b]	--	--	--	--	--	1.9Cu, 0.30Cb+Ta	**N06985**
Hastelloy G-30	Bal	30.0	1.5	5.0	0.03	1.5	1.0	5.5	2.5	1.5	1.8	--	--	--	--	**N06030**
Hastelloy G 50	Bal.	20.0	17.5	2.5	0.02	1.0	1.0	9.0	1.0	0.5	--	0.4	-	--	0.5Cu	
Hastelloy N	72.0	7.0	5.0[b]	--	0.06	--	--	16.0	--	--	0.5[b]	--	--	--	--	**N10003**
Hastelloy S	Bal	15.5	3.0[b]	2.0[b]	0.02[b]	0.50	0.40	14.5	1.0[b]	--	--	0.2	0.009	--	0.02La	**N06635**
Hastelloy W	61.0	5.0	5.5	2.5[b]	0.12[b]	--	--	24.5	--	--	--	--	--	--	0.6V	**N10004**
Hastelloy X	Bal	22.0	18.5	1.5	0.10	1.0[b]	1.0[b]	9.0	0.6	--	--	--	--	--	--	**N06002**
Hastelloy HX	Bal	22.0	20[b]	2.5[b]	0.15[b]	1.0	1.0	10.0[b]	1.0[b]	--	--	--	--	--	--	
Haynes 75	Bal	20	5.0	5--	0.11	1.0	1.0	--	--	--	0.4	--	--		0.5Cu	
Haynes 230	Bal	22.0	3.0	5.0	0.10	0.5	0.4	2.0	14.0	--	--	0.3	0.005	--	0.02La	**N06230**
Haynes 214™	Bal	17.6	3.0	--	0.05	0.5	0.2	--	--	--	--	4.5	0.01	0.1	0.01Y	**N07214**
Haynes 242	Bal	8.0	2	2.5	0.03	0.8	0.8	25	--	--	--	0.5	0.006	--	0.5 Cu	**--**
Haynes R-41	Bal	19	5[b]	11	0.09	0.1[b]	0.5[b]	10	--	--	3.1	1.5	0.006	--	--	**N07041**
Haynes HR-160	Bal	28	2.0	29	0.05	--	2.75	--	--	--	--	--	--	--	--	**N12160**
HAD 8077	Bal	16	--	--	--	--	--	--	--	--	--	4.0	--	--	--	
Illium Gc	Bal	22.0	5	--	0.20	--	--	6	--	--	--	--	--	--	6Cu	**--**

Alloys[a]	Nominal composition, wt%															UNS
	Ni	Cr	Fe	Co	C	Mn	Si	Mo	W	Cb	Ti	Al	B	Zr	Others	
Illium 98c	Bal	28.0	--	--	0.05	--	--	8	--	--	--	--	--	--	5Cu	**--**
Illium B[c]	Bal	28.0	--	--	0.05	--	3.5	8	--	--	--	--	--	--	5Cu	**--**
Illium W[c]	Bal	16.0	6.0	--	0.08	--	--	17	4	--	--	--	--	--	--	**--**
IN-100	Bal	10.0	--	1.5	0.18	--	--	3.0	--	--	4.7	5.5	0.014	0.06	1.0V	**--**
In-102	Bal	15.0	7.0	--	0.06	0.75[b]	0.4[b]	2.9	3.0	2.9	0.5	0.5	0.005	0.03	0.02Mg	
IN-162[c]	Bal	10.0	0.5[b]	--	0.12	0.10[b]	0.20[b]	4.0	2.0	1.0	1.0	6.5	0.020	0.10	2.0Ta	
IN-587	47.2	28	--	20.0	0.05	--	--	--	--	--	2.3	1.2	0.003	0.05	--	
IN-597	48.4	24.5	--	20.0	0.05	--	--	1.5	--	--	3.0	1.5	0.012	0.05	0.02Mg	
IN-643[c]	Bal	25.0	3.0	12.0	0.50	--	--	0.5	9.0	2.0	0.25	--	--	0.25	--	
IN-657[c]	50	50								1.0						
IN-731[c]	Bal	9.5	0.5[b]	10	0.18	0.2[b]	0.2[b]	2.5	--	--	4.65	5.5	0.015	0.06	0.95V	
IN-738[c]	Bal	16.0	0.5[b]	8.5	0.17	0.2[b]	0.3[b]	1.75	2.6	0.9	3.4	3.4	0.01	0.10	1.75Ta	
IN-792[c]	Bal	12.7	--	9.0	0.21	--	--	2.0	3.9	--	4.2	3.2	0.02	0.10	3.9Ta	
IN-853	74.6	20.0	--	--	0.05	--	--	--	--	--	2.5	1.5	0.007	0.07	1.3 Y_2O_3	
IN-939	Bal	22.5	0.5[b]	19.0	0.15	0.2[b]	0.2[b]	--	2.2	--	3.7	2.0	0.014	0.14	1.1Nb, 1.4Ta	
IN MA-6000E	68.5	15.0	--	--	0.05	--	--	2.0	4.0	--	2.5	4.5	0.01	0.15	1.1 Y_2O_3, 2.0Ta	
Inconel MA 754	78.5	20.0	--	--	0.05	--	--	--	--	--	0.5	0.3	--	--	0.6 Y_2O_3	**N07754**
Inconel MA 758	Bal	30.0	1.0	--	0.05	--	--	--	--	--	0.5	0.3	--	--	0.6 Y_2O_3	**--**

Alloys[a]	**Nominal composition, wt%**															**UNS**
	Ni	**Cr**	**Fe**	**Co**	**C**	**Mn**	**Si**	**Mo**	**W**	**Cb**	**Ti**	**Al**	**B**	**Zr**	**Others**	
Inconel 600	76.0	15.5	8.0	--	0.08	0.5	0.2	--	--	--	--	--	--	--	0.2Cu	**N06601**
Inconel 601	60.5	23.0	14.1	--	0.05	0.5	0.2	--	--	--	--	1.4	--	--	0.2Cu	**N06601**
Inconel 617	52.0	22.0	1.5	12.5	0.1	0.5	0.5	9.0	--	--	0.3	1.2	--	--	0.2Cu	**N06617**
Inconel 622	Bal	21.0	4.0	2.5[b]	0.015[b]	0.5[b]	0.08[b]	13.5	--	--	--	--	--	--	0.35[b]V	**N06022**
Inconel 625	61.0	21.5	2.5	--	0.05	0.2	0.2	9.0	--	3.6	0.2	0.2	--	--	--	**N06625**
Inconel 671	53.5	46.0	--	---	0.05	--	--	--	--	--	0.4	--	--	--	--	**--**
Inconel 686	Bal	21.0	1.0[b]	--	0.01[b]	0.75[b]	0.08[b]	16.0	3.7	--	0.02	--	--	--	--	**N06686**
Inconel 690	61.0	29.0	9.0	--	0.02	0.2	0.2	--	--	--	--	--	--	--	0.2Cu	**N06690**
Inconel 706	52.5	16.0	40.0	--	0.03	0.2	0.2	--	--	2.9	1.8	0.2	--	--	0.2Cu	**N09706**
Inconel 718	73.0	18.5	18.5	--	0.04	0.2	0.2	3.0	--	5.1	0.9	0.5	--	--	0.2Cu	**N07718**
Inconel 725™	57.0	21.0	~12.0	--	0.03b	0.35b	0.20b	8.3	--	--	1.4	0.35b	--	--	--	**N07725**
Inconel 751	Bal	15.5	7.0	--	0.05	0.5	0.2	--	--	1.0	2.3	1.2	--	--	0.2Cu	**--**
Inconel 783	28.0	3.0	25.5	Rem	0.10[b]	--	0.50[b]	--	--	--	0.2	5.4	0.008	--	3.0Nb, 0.50[b]Cu	**--**
Inconel X-750	72.5	15.5	7.0	--	0.04	0.5	0.2	--	--	1.0	2.5	0.7	--	--	0.2Cu	**N07754**
M-252, J1500 (Carpenter)	Bal	19.0	--	10	0.15	0.5[b]	0.5[b]	10	--	--	2.6	1.0	0.005	--	--	
MAR-M246[c]	Bal	9.0	0.15	10	0.15	0.10	0.05	2.5	10.0	--	1.5	5.5	0.015	0.05	1.5Ta, 0.1Cu	
MAR-M247	59.0	8.25	0.5[b]	10.0	0.15	--	--	0.7	10.0	--	1.0	5.5	0.015	0.05	1.5Hf, 3.0Ta	
MAR-M421[c]	Bal	15.5	1.0[b]	10	0.15	0.20[b]	0.20[b]	1.75	3.5	1.75	1.75	4.25	0.015	0.05	--	

Alloys[a]	Nominal composition, wt%														UNS
	Ni	Cr	Fe	Co	C	Mn	Si	Mo	W	Cb	Ti	Al	B	Zr	Others	
MAR-M432[c]	Bal	15.5	--	20	0.15	--	--	--	3.0	2.0	4.3	2.8	0.015	0.05	2.0Ta	
MM-004[c]	Bal	12.0	--	--	0.05	--	--	4.5	--	2.0	0.6	5.9	0.010	0.10	1.3Hf	
MM-008[c]	Bal	14.6	--	15.2	0.07	--	--	4.4	--	--	3.35	4.3	0.015	0.03	1.3Hf	
NA-224	48.0	27.0	18.5	--	0.50	--	--	--	6.0	--	--	--	--	--	--	
Nicrofer 6025HT-602CA	Bal	25.0	9.5	--	0.20	0.1	0.5	0.5	--	--	--	0.15	2.1	--	--	
Nicrotung[c]	Bal	12.0	--	10	0.10	--	--	--	8	--	4	4	0.050	0.05	--	**N06025**
Nimonic 75	78.8	20.0	--	--	0.01	0.1	0.70	--	--	--	0.4	--	--	--	--	**N06075**
Nimonic 86	65.0	25.0	--	--	--	--	--	10.0	--	--	--	--	--	--	0.03Ce	**--**
Nimonic 80	Bal.	19.5	3.0b	2.0b	0.1b	1.0b	1.0b	--	--	--	2.25	1.4	0.008b	0.15b	--	
Nimonic 80A	74.7	19.5	--	1.1	0.06	0.10	0.70	--	--	--	2.5	1.3	--	--	--	**N07080**
Nimanic 81	Bal	30									1.8	1.0				
Nimonic 90	57.4	19.5	--	18.0	0.07	0.50	0.70	--	--	--	2.4	1.4	--	--	--	**N07090**
Nimonic 95	53.5	19.5	5.0[b]	18.0	0.15[b]	--	--	--	--	--	2.9	2.0	+	+	--	
Nimonic 100	56.0	11.0	2.0[b]	20.0	0.30[b]	--	--	5.0	--	--	1.5	5.0	+	+	--	
Nimonic 101	Bal	24.2	--	19.7	0.1[b]	1.0[b]	1.0[b]	1.5	--	--	3.0	1.4	0.012	0.05	0.5[b]Cu	**--**
Nimonic 105	Bal	14.8	1.0[b]	20.0	0.12[b]	1.0[b]	1.0[b]	5.0	--	--	--	4.7	0.007	0.15[b]	0.2[b]Cu	**--**
Nimonic 115	Bal	15.0	1.0[b]	14.0	0.16	1.0[b]	1.0[b]	4.0	--	--	4.0	5.0	0.002	0.15[b]	0.2[b]Cu	**--**
Nimonic 263 **RollsRoyce263**	Bal	20.0	07[b]	20.0	0.06	06[b]	0.4[b]	5.9	--	--	2.2	2.6 (+Ti)	0.005	--	0.2[b]Cu	**N07263**
Nimonic 901	42.7	13.5	34	--	0.05	0.4	0.4	6.2	--	--	2.5	0.2	--	--	--	**N09901**

Alloys[a]	Nominal composition, wt%															UNS
	Ni	Cr	Fe	Co	C	Mn	Si	Mo	W	Cb	Ti	Al	B	Zr	Others	
Nimonic PE.11	39.0	18.0	33.5	1.0	0.05	--	--	--	--	--	2.35	0.85	--	--	--	
Nimonic PE 16	43.5	16.0	--	2.0[b]	0.06	0.2[b]	0.5[b]	3.3	--	--	1.2	1.2	0.005	0.03	0.5[b]Cu	**--**
Nimonic PK 33	Bal	18.0	1.0[b]	14.0	0.07[b]	0.5[b]	0.5[b]	7.0	--	--	2.3	2.1	0.005[b]	0.06[b]	0.2[b]Cu	**--**
Pyromet 680	Bal	21.5	18.5	1.50	0.75	1.00[b]	1.00[b]	9.00	0.60	--	--	--	--	--	0.04P[b] 0.03S[b]	**N06002**
RA-333	Bal	25.0	18	3.0	0.05	1.5	1.25	3.0	3.0	--	--	--	--	--	--	
Rene 41	Bal	19.0	--	11	0.09	--	--	10	--	--	3.1	1.5	0.010[b]	--	--	**N07041**
Rene 77[d]	Bal	15.0	1.0[b]	18.5	0.15[b]	--	--	5.2	--	--	3.5	4.25	0.05[b]	--	--	**--**
TDNiC	78.0	20.0	--	--	--	--	--	--	--	--	--	--	--	--	2.0ThO_2	
SEL	Bal	15.0	1.0[b]	26	0.08	0.3[b]	0.5[b]	4.5	--	--	2.4	4.4	0.015	--	--	
SEL-15	Bal	11.0	0.5[b]	14.5	0.07	0.3[b]	0.5[b]	6.5	1.5	0.5	2.5	5.4	0.015	--	--	
TRW 1800[c]	Bal	13.0	--	--	0.09	--	--	--	9.0	1.5	0.6	6.0	0.07	0.07	--	
TRW 1900[c]	Bal	10.3	--	10.0	0.11	--	--	--	9.0	1.5	1.0	6.3	0.03	0.10	--	
Udimet 500	Bal	19.0	0.5[b]	18.0	0.08	--	--	4	--	--	3.0	3.0	0.007	--	--	**N07500**
Udimet 520	Bal	19.0	--	12.0	0.05	--	--	6	1.0	--	3.0	2.0	0.005	--	--	
Udimet 630	Bal	17.0	17.5	1.0[b]	0.04	0.2[b]	0.2[b]	3.1	3.0	6.0	1.1	0.6	0.005	--	--	
Udimet 700	Bal	15.0	0.5[b]	18.5	0.07	0.2[b]	--	5.0	--	--	3.5	4.4	0.025	--	--	**--**

Alloys[a]	Nominal composition, wt%															UNS
	Ni	**Cr**	**Fe**	**Co**	**C**	**Mn**	**Si**	**Mo**	**W**	**Cb**	**Ti**	**Al**	**B**	**Zr**	**Others**	
Udimet 710	Bal	18.0	0.5[b]	14.7	0.07	--	0.2[b]	3.0	1.5	--	5.0	2.5	0.02	--	--	--
Udimet 720	Bal	18.0	--	14.7	0.035	0.1[b]	--	3.0	1.25	--	5.0	2.50	0.033	0.030	--	--
Unitemp 1753	Bal	16.25	9.5	7.2	0.24	0.05	0.10	1.6	8.4	--	3.2	1.9	0.008	0.06	.03S[b], 0.1Cu[b]	
Unitemp AF2-1DA	59.0	12.0	0.5b	10.0	0.16	--	--	3.0	6.0	--	3.0	4.6	0.015	0.10	--	
Waspaloy A[e]	Bal	19.5	2.0[b]	13.5	0.07	0.5[b]	0.5[b]	4.3	--	--	3.0	1.4	0.006	0.09	.02S[b], 0.1Cu[b]	
Waspaloy B[e]	Bal	19.5	2.0[b]	13.5	0.07	0.75[b]	0.75[b]	4.3	--	--	3.0	1.4	0.006	0.07	--	*N07001*

Notes:

a. Some superalloys such as Inconel 718, Rene 41, Udimet 500, and others are made by more than one manufacturer;
b. Maximum composition;
c. Cast alloy.
d. Compositions of Astroloy, Rene 77, and Udimet 700 are very similar. Certain elements are controlled to prevent sigma phase formation.
e. Waspaloy A has a higher solution temperature and longer time at stabilization than Waspaloy B.

Note:

1) Many of the alloy designations are registered trademarks of producer companies. For example, Hastelloy, Haynes, and Multimet are registered trademarks of Cabot Co., and Incoloy and Inconel are trade marks of Huntington Alloys Co.
2) The Unified Numbering System (**UNS**) is being developed jointly by the U.S. Society of Automotive Engineers (SAE) and the American Society of Testing and Materials (ASTM). Each UNS number consists of a single letter prefix followed by five digits. The interested high-temperature alloys appearing here fall into four different UNS material groups and may have prefixes of K, N, R, and S. The prefixes K, N, R and S represent the following UNS number series:
   Kxxxxx: miscellaneous steels and ferrous metals;
   Nxxxxx: nickel and nickel alloy;
   Rxxxxx: reactive and refractory metals and alloys;
   Sxxxxx: heat and corrosion resistant (stainless) steels.

Fe-Ni-Cr Base Alloys

Alloys[a]	Nominal composition, wt%															UNS
	Ni	Cr	Fe	Co	C	Mn	Si	Mo	W	Cb	Ti	Al	B	Zr	Others	
Armco 20-45-5	45.0	20.0	Bal	--	0.05	1.40	0.40	2.25	--	0.15	--	--	--	--	--	
CG-27	38	13	Bal	--	0.05	0.1	0.1	5.5	--	0.6	2.5	1.5	0.01	--	--	
CRM 6D[c]	5.0	22	Bal	--	1.05	5.00	0.50	1.0	1.0	1.0	--	--	0.003	--	--	
CRM 15D[c]	5.0	20	Bal	--	1.00	5.00	0.50	2.0	2.0	2.0	--	--	0.003	--	0.20N	
CRM 17D[c]	5.0	20	Bal	--	0.70	5.00	0.50	1.0	1.0	2.0	--	--	0.003	--	0.20N	
CRM 18D[c]	5.0	23	Bal	5.0	0.75	5.00	0.50	1.0	1.0	2.0	--	--	0.003	--	0.25N	
D-979	45	15	rem	--	0.05	0.75b	0.75b	4.0	4.0	--	3.0	1.0	0.01	--	--	
Discaloy	26	13.5	Bal	--	0.04	0.9	0.8	2.75	--	--	1.75	0.10	--	--	--	
Duraloy ”HOM-3”[c]	45.5	25.5	Bal	3.25	0.50	0.80b	1.0	3.25	3.25	--	--	--	--	--	--	
Illium P[c]	8	28	Bal	--	0.20	--	--	2.0	--	--	--	--	--	--	3 Cu	**--**
Illium PD[c]	5	27	Bal	7	0.08	--	--	2.0	--	--	--	--	--	--	--	**--**
Incoloy 020	35.0	20	Bal	--	--	2.0[b]	--	2.5	--	--	--	0.07b	--	--	3.5Cu	
Incoloy 028	31.5	27	Bal	--	0.03[b]	2.5[b]	1.0[b]	3.5	--	--	--	--	--	--	1.0Cu	
Incology A-286	25.5	15.0	Bal	--	0.08[b]	--	1.0[b]	1.25	--	--	2.20	0.35[b]	0.005	--	0.3[b]V	**S66286**
Incology 330	35.5	19.5	Bal	--	0.08[b]	2.0[b]	0.5[b]	6.5	--	--	--	--	--	--	1.0Cu	

Alloys[a]	Nominal composition, wt%															UNS
	Ni	Cr	Fe	Co	C	Mn	Si	Mo	W	Cb	Ti	Al	B	Zr	Others	
Incoloy 556	20.0	22.0	Bal	18.0	0.10	1.0	0.4	3.0	2.5	--	--	0.2	--	0.02	0.6Ta, 0.02La	**R30556**
Incoloy 800	32.5	21	46	--	0.08	0.8	0.5	--	--	--	0.4	0.4	--	--	0.4 Cu	**N08800**
Incoloy 801	32	20.5	44.5	--	0.05	0.8	0.5	--	--	--	1.1	--	--	--	0.2 Cu	**N08801**
Incoloy 802	32.5	21	46	--	0.4	0.8	.4	--	--	--	--	--	--	--	0.4 Cu	**N08802**
Incoloy 803	34.5	27.0	Bal	--	0.08	1.50[b]	1.0[b]	--	--	--	0.40	0.4	--	--	0.75[b]Cu	**--**
Incoloy 825	42	21.5	30	--	0.03	0.5	0.2	3.0	--	--	0.9	0.1	--	--	2.2 Cu	**N08825**
Incoloy 840	20.0	20.0	60.0	--	--	--	--	--	--	--	--	--	--	--	--	**--**
Incoloy 864	34.0	22.5	Bal	--	0.08b	1.0b	0.8	4.4	--	--	0.7	--	--	--	--	**S35135**
Incoloy 925	44.0	21.0	28.0	--	0.01	--	--	3.0	--	--	2.1	0.3	--	--	--	**N09925**
Incoloy DS	38.0	18.0	--	--	0.10b	1.2	2.3	--	--	--	0.2[b]	--	--	--	0.50[b]Cu	
Incoloy MA 956	0.50[b]	20	Bal	0.30[b]	0.10[b]	0.30[b]	--	--	--	--	0.5	4.5	--	--	0.5Y_2O_3	
N-155, Multimet alloy	20	21	Bal	20	0.10	1.5	0.5	3.0	2.5	1.0 (+Ta)	--	--	--	--	0.15 N, 0.50 Cu[b]	**R30155**
Pyromet 860 (carpenter)	44	13	Bal	4.0	0.05	0.25	0.10	6.0	--	--	3.0	1.0	0.01	--	--	**--**
Pyromet 31 (carpenter)	55.5	22.7	Bal	--	0.04	0.2[b]	0.2[b]	2.0	--	1.1	2.5	1.5	0.005	--	0.015P[b] 0.015S[b]	**N07031**
S-590	20	20.5	Bal	20	0.43	1.25	0.40	4.0	4.0	4.0	--	--	--	--	--	
Unitemp 212	25.0	16.0	Bal	--	0.08	0.05	0.15	--	--	0.50	4.0	0.15	0.06	0.05	--	
Pyromet V-57	27	14.8	Bal	--	0.08b	0.35b	0.75b	1.25	--	--	3.0	0.25	0.01	--	0.5 V[b]	**--**
W-545	26	13.5	Bal	--	0.08b	1.50	0.40	1.5	--	--	2.85	0.20	0.08	--	--	
16-25-6	25	16	Bal	--	0.08b	1.35	0.70	6.0	--	--	--	--	--	--	0.15 N	

Alloys[a]	Nominal composition, wt%															UNS
	Ni	**Cr**	**Fe**	**Co**	**C**	**Mn**	**Si**	**Mo**	**W**	**Cb**	**Ti**	**Al**	**B**	**Zr**	Others	
17-14CuMo	25.0	16.0	Bal	--	0.06	0.75	0.50	2.50	--	--	0.3	--	--	--	3.5Cu	
19-9DL	9.0	19	Bal	--	0.30	1.10	0.60	1.25	1.20	0.40	0.30	--	--	--	--	**K63198**
19-9DX	9.0	19	Bal	--	0.30	1.00	0.55	1.50	1.20	--	0.55	--	--	--	--	**K63199**
20Mo-4	37.5	23.75	Bal	--	0.03	1.0	0.5	4.25	--	--	--	--	--	--	0.5~1.5 Cu	**N08024**
20Mo-6	35.1	24.0	Bal	--	0.03	1.0	0.5	5.85	--	--	--	--	--	--	20~4.0 Cu	**N08026**
25-6Mo	25.0	20.0	Bal.	2.00[b]	0.02[b]	0.5[b]	6.5	--	--	--	--	--	--	--	2.0Cu	**N08926**
Aktiebolag 253 MA	11	21	Bal	--	0.08	--	1.7	--	--	--	--	--	--	--	0.04Ce 0.17N	
Haynes **HR-120**	37	25	Bal		0.05	--	--	--	--	--	--	--	--	--	0.7Nb 0.2N	**N08120**

a. Some alloys are made by more than one manufacturer
b. Maximum composition
c. Cast alloy.

Standard Stainless Steels

Alloys[a]	Nominal composition, wt%														UNS
	Ni	Cr	Fe	Mo	C	Mn	Si	Al	P	S	Ti	Cu	N	Others	
Austenitic types (Cr-Mn-Ni types-200 Series, and Cr-Ni-300 Series)															
201	4.5	17.0	Bal	--	0.15	6.5	1.00	--			--	--	0.25		**S20100**
202	5.0	18.0	Bal	--	0.15	8.75	1.00	--	0.06	0.03	--	--	0.25		**S20200**
301	7.0	17.0	Bal	--	0.15[b]	2.0[b]	0.75	--	0.045[b]	0.03[b]	--	--	0.10[b]		**S30100**
302	9.0	18.0	Bal	--	0.15	2.0	1.00	--	0.045	0.03	--	--	--		**S30200**
303	9.0	18.0	Bal	0.6	0.15	2.0	1.00	--	0.20	0.15[b]	--	--	--		**S30300**
304	9.25	18.0	Bal	--	0.08	2.0	1.00	--	0.045	0.03	--	--	--		**S30400**
305	12.75	18.0	Bal	--	0.12	2.0	1.00	--	0.045	0.03	--	--	--		**S30500**
308	13.5	20.0	Bal	--	0.08	2.0	1.00	--	0.045	0.03	--	--	--		**S30800**
309	13.5	23.0	Bal	--	0.20	2.0	1.00	--	0.045	0.03	--	--	--		**S30900**
310	20.5	25.0	Bal	--	0.25	2.0	1.50	--	0.045	0.03	--	--	--		**S31000**
314	20.5	24.5	Bal	2.50	0.25	2.0	2.25	--	0.045	0.03	--	--	--		**S31400**
316	12.0	17.0	Bal	--	0.08	2.0	1.00	--	0.045	0.03	--	--	--		**S31600**
317	13.5	19.0	Bal	3.5	0.08	2.0	1.00	--	0.045	0.03	--	--	--		**S31700**

Cont. "Standard Stainless Steels"

Alloys[a]	Nominal composition, wt%														UNS
	Ni	**Cr**	**Fe**	**Mo**	**C**	**Mn**	**Si**	**Al**	**P**	**S**	**Ti**	**Cu**	**N**	Others	
Austenitic types (Cr-Mn-Ni types-200 Series, and Cr-Ni-300 Series)															
321	10.5	18.0	Bal	--	0.08	2.0	1.00	--	0.045	0.03	0.50	--			**S32100**
329	4.5	27.5	Bal	1.5	0.10	2.0	1.00	--	0.045	0.03	--	--			**S32900**
330	35.5	18.5	Bal	--	0.08	2.0	1.25	--	0.04	0.03	--	--			**S33000**
334	19.5	19.5	Bal	--	0.03	1.0	0.75	--	0.02	0.015	--	--			**S33400**
347	11.0	18.0	Bal	--	0.08	2.0	1.00	--	0.045	0.03	--	--			**S34700**
348	11.0	18.0	Bal	--	0.08	2.0	1.00	--	0.045	0.03	--	0.2		0.8 Nb+Ta	**S34800**
Ferritic types (non-hardenable)															
405	--	13.0	Bal	--	0.08	1.00	1.00	0.20	0.04	0.04	0.5	--			**S40500**
409	--	11	Bal	--	0.08	1.00	1.00	--	0.045	0.045	--	--			**S40900**
429	--	15	Bal	--	0.12	1.00	1.00	--	0.03	0.03	--	--			**S42900**
430	--	17	Bal	--	0.12	1.00	1.00	--	0.03	0.03	--	--			**S43000**
434	--	17	Bal	1.0	0.12	1.00	1.00	--	0.04	0.03	--	--			**S43400**
436	--	17	Bal	1.0	0.12	1.00	1.00	--	0.04	0.03	--	--		0.6 Nb+Ta	**S43600**
442	--	20.5	Bal	--	0.20	1.00	1.00	--	0.04	0.03	--	--			**S44200**
443	--	20.5	Bal	--	0.20	1.00	1.00	--	0.04	0.03	--	1.1			**S44300**
446	--	25	Bal	--	0.20	1.50	1.00	--	0.04	0.03	--	--	0.25		S44600

I. Martensitic types (hardenable)																
410	--	12.0	Bal	--	0.15	1.00	1.00	--	0.04	0.03	--	--				**S41000**
420	--	13.0	Bal	--	0.15	1.00	1.00	--	0.04	0.03	--	--				**S42000**
440A	--	17.0	Bal	0.75	0.68	1.00	1.00	--	0.04	0.03	--	--				**S44002**
440B	--	17.0	Bal	0.75	0.85	1.00	1.00	--	0.04	0.03	--	--				
440C	--	17.0	Bal	0.75	1.10	1.00	1.00	--	0.04	0.03	--	--				**S44004**
504	--	9.0	Bal	1.0	0.15	1.00	1.00	--	0.04	0.04	--	--				
II. Precipitation hardening (Typically Cr% <18.0)																
630	4.0	16.3	Bal	--	0.07[b]	1.0[b]	1.0[b]	--	0.04b	0.03b	--	4.0	--		0.30 Cb+Ta	**S17400**
633	4.5	16.5	Bal	2.9	0.09	0.85	0.50	--	0.04	0.03	--	--	0.10			

Note: Some austenitic stainless steels are already listed in previous Fe-Ni-Cr Tables. Included here are ferritic stainless steels and some austenitic compositions.

Nonstandard Stainless Steels

Alloys[a]	Nominal composition, wt%														UNS
	Ni	Cr	Fe	Mo	C	Mn	Si	Al	P	S	Ti	Cu	N	Others	
Austenitic types (Cr-Mn-Ni types-200 Series, and Cr-Ni-300 Series)															
308L	11.0	20.0	Bal	--	0.03	2.00	1.00	--	0.045	0.03	--	--			**S30883**
309S	13.3	23.0	Bal	--	0.08	2.00	1.00	--	0.045	0.03	--	--			**S30908**
332	32.0	21.5	Bal	--	0.04	1.00	0.50	--	0.045	0.03	--	--			**N08800**
20Cb-3	35.0	20.0	Bal	2.5	0.07	2.00	1.00	--	0.045	0.035	--	3.5		0.6Nb	**N08020**
Al-6X	24.5	21.0	Bal	6.5	0.03	2.00	1.00	--	0.030	0.003	--	--			**N08367**
AL 30	2.2	16.0	Bal	--		8.0		--			--	--	0.20		**S20400**
AL 33	3.0	18.5	Bal	--		14		--			--	--	0.27		**S24000**
AL 40 or AL219	6.0	21.0	Bal	2.0		9.0		--			--	--	0.30		**S21904**
AL 50 (XM-19) (22-13-5)	12.5	21.5	Bal	2.25	0.06	5.0	1.0	--	0.04	0.03	--	--	0.3	0.2Nb 0.2V	**S20910**
Carpenter 21Cr-6Ni-9Mn	6.50	21	Bal	--	0.03[b]	9.00	1.00[b]	--	0.04[b]	0.03[b]	--	--	0.27	--	**S21904**
Carpenter 22Cr-13Ni-5Mn	13.0	22	Bal	2.25	0.06[b]	5.00	1.00[b]	--	0.04[b]	0.03[b]	--	--	0.30	0.2Cb 0.2V	**N20910**
III. Ferritic types (non-hardenable)															
AL 29-4-2	2.1	29.0	Bal.	4.0	0.01	0.05	0.1	--	0.025	0.02	--	--	0.015		**S44800**
AL 29-4	0.15	29.0	Bal.	4.0	0.01	0.3	0.2	--	0.025	0.02	--	--			**S44700**
AL 29-4C	0.30	29.0	Bal.	4.0	0.02	0.5	0.35	--	0.03	0.01[b]	0.6[b]	--	0.02	0.6[b] Ti+Nb	**S44735**

Alloys[a]	Nominal composition, wt%														UNS
	Ni	Cr	Fe	Mo	C	Mn	Si	Al	P	S	Ti	Cu	N	Others	
Ferritic types (cont.)															
7-Mo Stainless (Car)	5.2	29.0	Bal.	2.5	0.03	2.0	0.6	--			--	--	0.35		**S32950** (duplex)
Alloy 255 (AL)	5.5	25.5	Bal.	3.5	0.04	1.5	1.0	--	0.04	0.03[b]	--	2.0	0.20		**S32550** (duplex)
E-Brite 26-1	0.09	26.0	Bal.	1.0	0.001	0.01	.025	--	0.02	0.02	--	0.03	0.01		**S44627**
Sea-cure/Sc-1	2.5	26.0	Bal	3.0	0.025	1.00	0.75	--	0.04	0.03	0.3	--			**S44660**
Kanthal (APM)	--	22	Bal	--		--	--	6.0			--	--			
AL 453™	0.3	22.0	Bal	--	0.03	0.3	0.3	0.6	0.02	0.03[b]	0.02	--		0.10[b] (Ce+La)	**--**
Carpenter 443	--	20.5	Bal	--	0.2[b]	1.0[b]	1.0[b]	--	0.04[b]	0.0[b]	--	--		1.0Cu	**S44300**
PM 2000	--	20	Bal	---	--	--	--	5.5	--	--	--	0.5		0.5Y_2O_3	
AL 433 ™	0.25	20.0	Bal	--	0.01	0.30	0.39	--	0.021	0.001	--	--	0.019	0.54 Cb, 0.80[b]	**S43300**
AL 444 ™ (Alloy 18-2)	1.00	18.5	Bal	2.10	0.025	1.00	1.00	--	0.04	0.03	0.4	--	0.035		**S44400**
Armco 18 SR	0.25	18.0	Bal.	--	0.015	0.30	1.0	2.0	--	--	0.4	--	0.25		
AL 468™	0.22	18.25	Bal	--	0.009	0.40	0.55	0.03	0.024	0.001	0.10	--	0.016	0.25 Cb	**S46800**
AL 441 HP™	0.30	18.0	Bal	--	0.009	0.35	0.34	0.05	0.023	0.002	0.29	--	0.014	0.71 Cb 0.8[b] Ti+Cb	
AL 439 HP™	0.23	18.0	Bal	--	0.012	0.45	0.55	--	0.02	0.001[b]	0.40	--	0.013		**S43035**
ODM 751	--	16.5	Bal	1.5	--	--	--	4.5	--	--	--	0.6		0.5Y_2O_3	
Fecralloy [d]		15.0~ 22.0	Bal.	--	0.03			4.0~ 5.2			--	--		0.05~0.5% Y	

Alloys[a]	Nominal composition, wt%														UNS
	Ni	Cr	Fe	Mo	C	Mn	Si	Al	P	S	Ti	Cu	N	Others	
IV. Martensitic types, hardenable															
410Cb (XM-30)	--	12.5	Bal	--	0.18	1.00	1.00	--	0.04	0.03	--	--		0.2 Nb	
V. Precipitation-hardening stainless steels															
Stainless W (635)	6.75	16.75	Bal	--	0.08	1.00	1.00	0.4	0.04	0.03	0.8	--	--		
Sealing-glass or Control-expansion Alloys *															
AL 430Ti		20.0	Bal												**R91800**
AL sealmet 485	47.0	6.0	Bal												**--**
Carpenter "18"	--	18.0	Bal	--	0.10	0.60	0.40	--			0.40	--			**--**
Carpenter "27"	0.5[b]	28.0	Bal	--	0.05	0.60	0.40	--			--	--			

a. Some alloys are made by more than one manufacturer;
b. Maximum composition;
c. Cast alloy
d. Fecralloy is a group of alloy, in which Fe, Cr, Al and rare earth elements are major alloying elements.

* For glass-to-metal sealing applications, the thermal expansion characteristics of glass and metal are closely matched and the metal must also have an oxide which fluxes at high temperature with the glass to provide a hermetic and mechanically sound joint.

Co Base Alloys

Alloys[a]	Nominal composition, wt%														UNS
	Ni	Cr	Fe	Co	C	Mn	Si	Mo	W	Cb	Ti	Al	B	Zr	Others	
AiResist 13c	1.0[b]	21	2.5[b]	Bal	0.45	0.5[b]	--	--	11	2.0	--	3.5	--	--	0.1Y	
AiResist 213	--	19	--	Bal	0.18	--	--	--	4.7	--	--	3.5	--	0.15	6.5Ta, 0.1Y	
AiResist 215[c]	--	19	--	Bal	0.35	--	--	--	4.5	--	--	4.3	--	0.13	7.5Ta, 0.17Y	
Elgiloy	15.0	20.0	Bal	40.0	0.15	2.0	--	7.0	--	--	--	--	--	--	0.04Be	
CM-7	15.0	20.0	--	48.0	0.10	--	--	--	15.0	--	1.3	0.5	--	--	--	
FSX-414[c]	10.5	29.5	2.0[b]	Bal	0.25	1.0[b]	1.0[b]	--	7.0	--	--	--	0.012	--	--	
FSX-418[c]	10.5	29.5	2.0[b]	Bal	0.25	1.0[b]	1.0[b]	--	7.0	--	--	--	0.012	--	0.15Y	
FSX-430[c]	10.0	29.5	--	Bal	0.40	--	--	--	7.5	--	--	--	0.027	0.9	0.5Y	
Haynes 21[c]	3	27	1	64	0.25	--	--	5	--	--	--	--	--	--	--	
Haynes 25 (WF-11, L 605)	10	20	3.0[b]	Bal	0.10	1.50	0.50	--	15	--	--	--	--	--	--	
Haynes 150	3.0[b]	28	20.0	Bal	0.08	0.65	0.35	1.5[b]	--	--	--	--	--	--	--	
Haynes 188	22	22	3.0[b]	Bal	0.10	1.25[b]	0.3	--	14	--	--	--	--	--	0.04La	R30188

Alloys[a]	Nominal composition, wt%															UNS
	Ni	**Cr**	**Fe**	**Co**	**C**	**Mn**	**Si**	**Mo**	**W**	**Cb**	**Ti**	**Al**	**B**	**Zr**	Others	
Haynes 6B (Stellite)	3.0	30.0	1.0	61.5	1.0	1.4	--	1.5	4.0	--	--	--	--	--	--	R30006
Haynes 6K (Stellite)	2.0	31.0	3.0b	59.0	1.6	2.0b	2.0b	1.50b	4.50	--	--	--	--	--	--	**R30006**
J-1570	28.0	20.0	2.0	46.0	0.2	--	--	--	--	--	4.0	--	--	--	--	
MAR-M302[c]	--	21.5	--	Bal	0.85	0.10	0.20	--	10.0	--	--	--	0.005	0.15	9.0Ta	
MAR-M322[c]	--	21.5	--	Bal	1.00	0.10	0.10	--	9.0	--	0.75	--	--	2.25	4.5Ta	
MAR-M509[c]	10	21.5	1.0	Bal	0.60	0.10[b]	0.10[b]	--	7.0	--	0.2	--	0.010[b]	0.50	3.5Ta	
MAR-M918	20	20	0.5[b]	Bal	0.05	0.2[b]	0.2[b]	--	--	--	--	--	--	0.10	7.5Ta	
MP35N	35.0	20.0	--	35.0	--	--	--	10.0	--	--	--	--	--	--	--	
MP 159	25.0	19.0	9.0	36.0	--	--	--	7.0	--	--	3.0	0.2	--	--	--	
NASA Co-W-Re[c]	--	3	--	Bal	0.40	--	--	--	25	--	1.0	--	--	1.0	2.0Re	
S-816	20	20	4	Bal	0.38	1.20	0.40	4.0	4.0	4.0	--	--	--	--	--	
TD Co	20.0	18.0	--	60.0	--	--	--	--	--	--	--	--	--	--	2.0ThO_2	
UMCo-50	--	28.0	21.0	49.0	0.12[b]	--	--	--	--	--	--	--	--	--	--	
ULTIMET	9	26	3	54	0.06	0.8	0.3	5.0	2.0	--	--	--	--	--	--	
V-36[c]	20	25	3	Bal	0.27	1.00	0.40	4.0	2.0	2.0	--	--	--	--	--	
WF-31	10	20	--	Bal	0.15	1.42	0.42	2.6	10.7	--	1.0	--	--	--	--	

Alloys[a]	Nominal composition, wt%															UNS
	Ni	Cr	Fe	Co	C	Mn	Si	Mo	W	Cb	Ti	Al	B	Zr	Others	
WI-52[c]	1.0[b]	21	2.0	Bal	0.45	0.50[b]	0.50[b]	--	11	2.0	--	--	--	--	--	
X-40[c]	10	25	1.5	Bal	0.50	0.50	0.50	--	7.5	--	--	--	--	--	--	
X-45[c]	10.5	25.5	2.0[b]	Bal	0.25	1.0[b]	--	--	7.0	--	--	--	0.010	--	--	

a. Some alloys are made by more than one manufacturer
b. Maximum composition
c. Cast alloy.

Cr Base Alloys

Alloys[a]	Nominal composition, wt%															UNS
	Ni	Cr	Fe	Co	C	Mn	Si	Mo	W	Cb	Ti	Al	B	Zr	Others	
C207	--	Bal	--	--	0.10	--	--	--	7.5	--	0.2	--	--	0.8	0.15Y	
CI-41	--	Bal	--	--	0.09	--	--	7.1	--	--	--	--	--	--	0.1 (Y+La) 2.0 Ta	
IM-15	--	Bal	--	--	--	--	--	--	--	--	--	--	0.1	--	1.7 Ta 0.1 Y	
Chrome 30	--	Bal	--	--	--	--	--	--	--	--	0.5	--	--	--	6MgO	
Chrome 90	--	Bal	--	--	--	--	0.5	--	--	--	--	--	--	--	3MgO, 2.5V	
Chrome 90s	--	Bal	--	--	0.5	--	1.0	--	--	--	0.5	--	--	--	3MgO, 2.5Ta	
Duraclloy (plansee)	--	Bal	5.0	--	0.002	--	--	--	--	--	--	--	--	--	1.0 Y_2O_3, 0.006La, 0.001S, 0.0066N	

a. Some alloys are made by more than one manufacturer
b. Maximum composition
c. Cast alloy.

Appendix B
Selected Compositions
Ni-Cr or Ni-Cr-Fe Base Alloys

Alloys[a]	Nominal composition, wt%															Characteristics, Typical applications
	Ni	Cr	Fe	Co	C	Mn	Si	Mo	W	Cb	Ti	Al	B	Zr	Others	
Inconel 671	53.5	46.0	--	---	0.05	--	--	--	--	--	0.4	--	--	--	--	For extremely corrosive environments
IN-657[c]	50	50								1.0						
Inconel MA 758	Bal	30.0	1.0	--	0.05	--	--	--	--	--	0.5	0.3	--	--	0.6 Y_2O_3	MAed, furnace skid rails at 1260°C, fuel atomizer in diesel engine
Nimonic 81	Bal	30.0										1.0			2.0Cu	
Hastelloy G-30	Bal	30.0	1.5	5.0	0.03	1.5	1.0	5.5	2.5	1.5	1.8	--	--	--	--	Superior corrosion resistance
Inconel 690	61.0	29.0	9.0	--	0.02	0.2	0.2	--	--	--	--	--	--	--	0.2Cu	Resist nitric/hydrofluoric acid
IN-587	47.2	28	--	20.0	0.05	--	--	--	--	--	2.3	1.2	0.003	0.05	--	
Haynes HR-160	Bal	28	2.0	29	0.05	--	2.75	--	--	--	--	--	--	--	--	Developed for high temp. hot corrosion resistance
NA-224	48.0	27.0	18.5	--	0.50	--	--	--	6.0	--	--	--	--	--	--	
Nicrofer 6025HT-602CA	Bal	25.0	9.5	--	0.20	0.1	0.5	0.5	--	--	--	0.15	2.1	--	--	Excl. resist. To oxidation & carburising at high °C
Nimonic 86	65.0	25.0	--	--	--	--	--	10.0	--	--	--	--	--	--	0.03Ce	Combustion chamber, excep. Oxidation & scaling resistance
RA-333	Bal	25.0	18	3.0	0.05	1.5	1.25	3.0	3.0	--	--	--	--	--	--	Turbine parts, radiant tubes
IN-597	48.4	24.5	--	20.0	0.05	--	--	1.5	--	--	3.0	1.5	0.012	0.05	0.02Mg	Stressed parts in turbines, Excl. oxidation & corrosion resistance (>900°C)

Alloys[a]	Nominal composition, wt%															Characteristics, Typical applications
	Ni	Cr	Fe	Co	C	Mn	Si	Mo	W	Cb	Ti	Al	B	Zr	Others	
Nimonic 101	Bal	24.2	--	19.7	0.1[b]	1.0[b]	1.0[b]	1.5	--	--	3.0	1.4	0.012	0.05	0.5[b]Cu	Similar to IN 597
Inconel 601	60.5	23.0	14.1	--	0.05	0.5	0.2	--	--	--	--	1.4	--	--	0.2Cu	Furnace, heat treat fixtures
Hastelloy C-2000	Bal	23	--	--	0.01[b]	--	0.08[b]	16.0	--	--	--	--	--	--	1.6 Cu	Superior oxidation and corrosion resistance in both oxidizing and reducing environments. Developed for chemicals industries.
IN-939	Bal	22.5	0.5[b]	19.0	0.15	0.2[b]	0.2[b]	--	2.2	--	3.7	2.0	0.014	0.14	1.1Nb, 1.4Ta	Appls. In marine environment or less pure fuel.
Haynes 230	Bal	22.0	3.0	5.0	0.10	0.5	0.4	2.0	14.0	--	--	0.3	0.005	--	0.02La	Combination of strength, stability, oxidation and fabric ability Aero ducks, combustors
Hayness 556	21.0	22.0	29.0	20.0	0.10	--	--	3.0	2.5	--	--	0.3	--	0.002	0.02La, 0.50Ta	
Inconel 617	52.0	22.0	1.5	12.5	0.1	0.5	0.5	9.0	--	--	0.3	1.2	--	--	0.2Cu	Gas turbine aircraft engine parts
Hastelloy G	Bal	22.0	19.5	2.5[b]	0.05[b]	1.5	1.0[b]	6.5	1.0[b]	--	0.7[b]	--	--	--	2.0Cu, 2.0Cb+Ta	Resists pitting and stress-corrosion cracking
Hastelloy G-3	Bal	22.0	19.5	5.0[b]	0.015[b]	0.80	0.40	7.0	1.5[b]	--	--	--	--	--	1.9Cu, 0.30Cb+Ta	Phosphoric acid service
Hastelloy X	Bal	22.0	18.5	1.5	0.10	1.0[b]	1.0[b]	9.0	0.6	--	--	--	--	--	--	Engine sheet parts, good oxidation resistance
Hastelloy HX	Bal	22.0	20b	2.5b	0.15[b]	1.0	1.0	10.0[b]	1.0[b]	--	--	--	--	--	--	
Pyromet 680	Bal	21.5	18.5	1.50	0.75	1.00[b]	1.00[b]	9.00	0.60	--	--	--	--	--	0.04P[b] 0.03S[b]	Turbine rotors, shafts; furnaces, chemical industry
Hastelloy C-22	51.6	21.5	5.5	2.5	0.01	1.0	0.1	13.5	4.0	--	--	--	--	--	0.3V	Superior weldability, used as overalloy filler to improve corrosion resistance
Inconel 625	61.0	21.5	2.5	--	0.05	0.2	0.2	9.0	--	3.6	0.2	0.2	--	--	--	Aircraft engines/structures, chemical processing
Inconel 622	Bal	21.0	4.0	2.5[b]	0.015[b]	0.5[b]	0.08[b]	13.5	--	--	--	--	--	--	0.35[b]V	Excl. resistance to oxidizing & reducing acidic environments.
Inconel 686	Bal	21.0	1.0[b]	--	0.01[b]	0.75[b]	0.08[b]	16.0	3.7	--	0.02	--	--	--	--	Used in the most severe environments in chemical processing, food production, etc.

Alloys[a]	Nominal composition, wt%															Characteristics, Typical applications
	Ni	**Cr**	**Fe**	**Co**	**C**	**Mn**	**Si**	**Mo**	**W**	**Cb**	**Ti**	**Al**	**B**	**Zr**	**Others**	
Hastelloy G 50	Bal.	20.0	17.5	2.5	0.02	1.0	1.0	9.0	1.0	0.5	--	0.4	-	--	0.5Cu	For appli. In severe sour gas env.
Hastelloy D-205 ™	Bal	20	6.0	--	0.03[b]	--	5.0	2.5	--	--	--	--	--	--	2.0Cu	Outstanding corrosion resistance to concentrated acidic media, silica forming alloy
Nimonic 263 RollsRoyce263	Bal	20.0	07[b]	20.0	0.06	06[b]	0.4[b]	5.9	--	--	2.2	2.6 (+Ti)	0.005	--	0.2[b]Cu	Turbine rings, casings
IN-853	74.6	20.0	--	--	0.05	--	--	--	--	--	2.5	1.5	0.007	0.07	1.3 Y_2O_3	
Inconel MA 754	78.5	20.0	--	--	0.05	--	--	--	--	--	0.5	0.3	--	--	0.6 Y_2O_3	MAed, turbine vanes
Inconel 050	50.0	20.0	18.0	2.5[b]	0.02[b]	1.0[b]	1.0[b]	9.0	1.0[b]	0.5[b]	--	0.4[b]	--	--	0.5[b]Cu	Oil tubular goods, Excl. corrosion resistance in a variety of enviro.
TDNiC	78.0	20.0	--	--	--	--	--	--	--	--	--	--	--	--	2.0ThO_2	
Nimonic 75	78.8	20.0	--	--	0.01	0.1	0.70	--	--	--	0.4	--	--	--	--	Sheet parts in turbines, nuclear engineering.
Haynes 75	Bal	20	5.0	5--	0.11	1.0	1.0	--	--	--	0.4	--	--		0.5Cu	Equivalent to alloy 600, low stress elevated temperature with reasonable oxidation resistance requirement.
Nimonic 95	53.5	19.5	5.0[b]	18.0	0.15[b]	--	--	--	--	--	2.9	2.0	+	+	--	
Nimonic 90	57.4	19.5	--	18.0	0.07	0.50	0.70	--	--	--	2.4	1.4	--	--	--	Turbine blades & discs, hot working tools
Waspaloy A[d]	Bal	19.5	2.0[b]	13.5	0.07	0.5[b]	0.5[b]	4.3	--	--	3.0	1.4	0.006	0.09	.02S[b], 0.1Cu[b]	Jet engine blades
Waspaloy B[d]	Bal	19.5	2.0[b]	13.5	0.07	0.75[b]	0.75[b]	4.3	--	--	3.0	1.4	0.006	0.07	--	Jet engine discs
Nimonic 80	Bal.	19.5	3.0b	2.0b	0.1b	1.0b	1.0b	--	--	--	2.25	1.4	0.008b	0.15b	--	Turbine blades, rings and discs.
Nimonic 80A	74.7	19.5	--	1.1	0.06	0.10	0.70	--	--	--	2.5	1.3	--	--	--	Turbine blades, rings and discs.
Udimet 500	Bal	19.0	0.5[b]	18.0	0.08	--	--	4	--	--	3.0	3.0	0.007	--	--	Gas turbine parts/sheets/bolts
Udimet 520	Bal	19.0	--	12.0	0.05	--	--	6	1.0	--	3.0	2.0	0.005	--	--	Similar to Udimet 500, improved workability

Alloys[a]	Nominal composition, wt%															Characteristics, Typical applications
	Ni	Cr	Fe	Co	C	Mn	Si	Mo	W	Cb	Ti	Al	B	Zr	Others	
Rene 41	Bal	19.0	--	11	0.09	--	--	10	--	--	3.1	1.5	0.010[b]	--	--	Jet engine blades, parts
M-252, J1500	Bal	19.0	--	10	0.15	0.5[b]	0.5[b]	10	--	--	2.6	1.0	0.005	--	--	Gas turbine blades, parts, sheets
Inconel 718	73.0	18.5	18.5	--	0.04	0.2	0.2	3.0	--	5.1	0.9	0.5	--	--	0.2Cu	Good weldability and fabricability Jet engine/rocket parts
Udimet 710	Bal	18.0	0.5[b]	14.7	0.07	--	0.2[b]	3.0	1.5	--	5.0	2.5	0.02	--	--	Sulfidation resistant disc alloy
Udimet 720	Bal	18.0	--	14.7	0.035	0.1[b]	--	3.0	1.25	--	5.0	2.50	0.033	0.030	--	Sulfidation/impact resistance gas turbine alloy
Nimonic PK 33	Bal	18.0	1.0[b]	14.0	0.07[b]	0.5[b]	0.5[b]	7.0	--	--	2.3	2.1	0.005[b]	0.06[b]	0.2[b]Cu	Gas turbine flame tubes
Nimonic PE.11	39.0	18.0	33.5	1.0	0.05	--	--	--	--	--	2.35	0.85	--	--	--	

f. Some superalloys such as inconel 718, Rene 41, Udimet 500, and others are made by more than one manufacturer.
g. Maximum composition
h. Compositions of Astroloy, Rene 77, and Udimet 700 are very similar. Certain elements are controlled to prevent sigma phase formation.
i. Waspaloy A has a higher solution temperature and longer time at stabilization than Waspaloy B.

Note: Many of the alloy designations are registered trademarks of producer companies. For example, Hastelloy, Haynes, and Multimet are registered trademarks of Cabot Co., and Incoloy and Inconel are trademarks of Huntington Alloys Co.

Fe-Ni-Cr Base Alloys

Alloys[a]	Nominal composition, wt%															Characteristics, Typical applications
	Ni	Cr	Fe	Co	C	Mn	Si	Mo	W	Cb	Ti	Al	B	Zr	Others	
Incoloy 028	31.5	27	Bal	--	0.03[b]	2.5[b]	1.0[b]	3.5	--	--	--	--	--	--	1.0Cu	Highly alloyed aus. SSS Excl. resistance to oxidizing & reducing environ.
Incoloy 803	34.5	27.0	Bal	--	0.08	1.50[b]	1.0[b]	--	--	--	0.40	0.4	--	--	0.75[b]Cu	Excl. high temperature corrosion resist.
Haynes HR-120	37	25	Bal		0.05	--	--	--	--	--	--	--	--	--	0.7Nb 0.2N	Developed recently for more improved creep rupture strength.
20Mo-4	37.5	23.75	Bal	--	0.03	1.0	0.5	4.25	--	--	--	--	--	--	0.5~1.5 Cu	
20Mo-6	35.1	24.0	Bal	--	0.03	1.0	0.5	5.85	--	--	--	--	--	--	2-4.0 Cu	
Pyromet 31 (carpenter)	55.5	22.7	Bal	--	0.04	0.2[b]	0.2[b]	2.0	--	1.1	2.5	1.5	0.005	--	0.015P[b] 0.015S[b]	A sulfidation and corrosion resistant precipitation hardenable alloy
Incoloy 864	34.0	22.5	Bal	--	0.08b	1.0b	0.8	4.4	--	--	0.7	--	--	--	--	Specially developed for auto-exhaust system.
Incoloy 556	20.0	22.0	Bal	18.0	0.10	1.0	0.4	3.0	2.5	--	--	0.2	--	0.02	0.6Ta, 0.02La	
Incoloy 825	42	21.5	30	--	0.03	0.5	0.2	3.0	--	--	0.9	0.1	--	--	2.2 Cu	Heat exchanger, condenser tubing, stress-corrosion resistance
Aktiebolag 253 MA	11	21	Bal	--	0.08	--	1.7	--	--	--	--	--	--	--	0.04Ce 0.17N	Developed lately for oxidation resistance
Incoloy 800	32.5	21	46	--	0.08	0.8	0.5	--	--	--	0.4	0.4	--	--	0.4 Cu	Furnace. Heat exchanger parts
Incoloy 925	44.0	21.0	28.0	--	0.01	--	--	3.0	--	--	2.1	0.3	--	--	--	Surface & down-hole hardware in sour gas wells
N-155, Multimet alloy	20	21	Bal	20	0.10	1.5	0.5	3.0	2.5	1.0 (+Ta)	--	--	--	--	0.15 N, 0.50 Cu[b]	Gas turbine sheet parts
Incoloy 802	32.5	21	46	--	0.4	0.8	.4	--	--	--	--	--	--	--	0.4 Cu	Titanium creep-forming dies, ethylene furnace tubes
S-590	20	20.5	Bal	20	0.43	1.25	0.40	4.0	4.0	4.0	--	--	--	--	--	Gas turbine parts, blades
Incoloy 801	32	20.5	44.5	--	0.05	0.8	0.5	--	--	--	1.1	--	--	--	0.2 Cu	Petroleum hydrotreaters, heat exchangers

Alloys[a]	Nominal composition, wt%															Characteristics, Typical applications
	Ni	Cr	Fe	Co	C	Mn	Si	Mo	W	Cb	Ti	Al	B	Zr	Others	
Incoloy 840	20.0	20.0	60.0	--	--	--	--	--	--	--	--	--	--	--	--	Specially developed for the seam-welded tubing
Armco 20-45-5	45.0	20.0	Bal	--	0.05	1.40	0.40	2.25	--	0.15	--	--	--	--	--	Heat exchanger, condenser tubing, tress-corrosion resis
Incology 25-6Mo	25.0	20.0	Bal.	0.02[b]	2.00[b]	0.5[b]	6.5	--	--	--	--	--	--	--	2.0Cu	Parts served in natural and acidic enviroments
Incoloy 020	35.0	20	Bal	--	--	2.0[b]	--	2.5	--	--	--	0.07[b]	--	--	3.5Cu	Excl. resistance in chloride, sulfuric, phosphoric & nitric acides
Incology 330	35.5	19.5	Bal	--	0.08[b]	2.0[b]	0.5[b]	6.5	--	--	--	--	--	--	1.0Cu	Similar to RA-330 or RA-330 HC Excl. corros. Resist. To natural & acidic environ.
19-9DL	9.0	19	Bal	--	0.30	1.10	0.60	1.25	1.20	0.40	0.30	--	--	--	--	Low-cost sheet, bar, forging alloy
19-9DX	9.0	19	Bal	--	0.30	1.00	0.55	1.50	1.20	--	0.55	--	--	--	--	Similar to 19-9DL, no columbium and tantalum
RA-330	35	19	43	--	0.05	1.5	1.25	--	--	--	--	--	--	--	--	Heat exchangers, radiant tubes, etc.
RA-330 HC	35	19	43	--	0.40	1.5	1.25	--	--	--	--	--	--	--	--	Higher strength than RA-330
Rolled Alloys RA85H	14.5	18.5	Bal	--	0.2	--	3.6	--	--	--	--	1.0	--	--	--	Specifically developed for carburization resistance
Incoloy DS	38.0	18.0	--	--	0.10b	1.2	2.3	--	--	--	0.2[b]	--	--	--	0.50[b]Cu	Good internal oxidation resistance due to addition of Si

d. Some alloys are made by more than one manufacturer;
e. Maximum composition;
f. Cast alloy.

Ferritic Stainless Steels

Alloys[a]	Nominal composition, wt%														Characteristics, Typical applications
	Ni	Cr	Fe	Mo	C	Mn	Si	Al	P	S	Ti	Cu	N	Others	
29-4-2 (AL)	2.1	29.0	Bal.	4.0	0.003	0.05	0.1	--	0.025	0.02	--	--	0.015		Superferritic, and high strength and corrosion resistance
29-4C (AL)	0.15	29.0	Bal.	4.0	0.01	0.3	0.2	--	0.025	0.02	--	--			Superferritic, high strength and corrosion resistance
7-Mo Stainless (Car)	5.2	29.0	Bal.	2.5	0.03	2.0	0.6	--			--	--	0.35		A duplex structure with 85% ferrite and 15% austenite.
Alloy 255 (AL)	6.5	27.0	Bal.	3.9	0.04	1.5	1.0	--			--	2.5	0.25		A duplex structure with 50% ferrite and 50% austenite. Designed for comb. of high strength and exc. coro. res.
E-Brite 26-1	0.09	26.0	Bal.	1.0	0.001	0.01	.025	--	0.02	0.02	--	0.03	0.01		Superferritic, high corrosion resistance
Sea-cure/Sc-1	2.5	26.0	Bal	3.0	0.025	1.00	0.75	--	0.04	0.03	0.3	--	--		Superferritic
Monit	4.5	26.0	Bal.	4.5	0.25	1.0	0.75	--	0.04	0.03	0.6	--	--		A duplex structure
26-1 Ti	0.50	26.0	Bal	1.00	0.06	0.75	0.75	--	0.04	0.02	0.6	0.2	0.04		
18-2FM	--	26.0	Bal	--	0.08	2.50	1.00	--	0.04	0.15	--	--	--		Free-machining alloy with corrosion resistance similar to that of 303
446	--	25	Bal	--	0.20	1.50	1.00	--	0.04	0.03	--	--	0.25		More Cr than 442 for more improved scaling resistance
Carpenter 443	--	20.5	Bal	--	0.2[b]	1.0[b]	1.0[b]	--	0.04[b]	0.0[b]	--	--	--	1.0Cu	Corrosion and mechanical properties close to 18-8 austenitic stainless steels
442	--	20.5	Bal	--	0.20	1.00	1.00	--	0.04	0.03	--	--	--		Equivalent to Carpenter 443
AL 453™	0.3	22.0	Bal	--	0.03	0.3	0.3	0.6	0.02	0.03[b]	0.02	--		0.10[b] (Ce+La)	For SOFC applications due to its TEC match and excellent oxidation and scaling resistance.

Ferritic stainless steels (cont.)

Alloys[a]	Nominal composition, wt%														Characteristics, Typical applications
	Ni	Cr	Fe	Mo	C	Mn	Si	Al	P	S	Ti	Cu	N	Others	
AL 433 ™	0.25	20.0	Bal	--	0.01	0.30	0.39	--	0.021	0.001	--	--	0.019	0.54 Cb, 0.80[b]	Superferritic, in the family of 409 and 439. Combining oxidation resistance and high temp. strength.
Carpenter 443	--	20.5	Bal	--	0..20	1.00	1.00	--	0.04[b]	0.03[b]	--	1.10	--		As modified type of 430 for higher corrosion resistance.
444 (18-2)	1.00	18.5	Bal	2.10	0.025	1.00	1.00	--	0.04	0.03	0.4	--	0.035		More Mo than 442 for higher corrosion resistance
AL 468™	0.22	18.25	Bal	--	0.009	0.40	0.55	0.03	0.024	0.001	0.10	--	0.016	0.25 Cb	Cb stabilized, reducing Ti and thus the Ti related defects as in 439
AL 441 HP™	0.30	18.0	Bal	--	0.009	0.35	0.34	0.05	0.023	0.002	0.29	--	0.014	0.71 Cb 0.8[b] Ti+Cb	Good oxidation and corrosion resistance for auto. Exhaust application.
AL 439 HP™	0.23	18.0	Bal	--	0.012	0.45	0.55	--	0.02	0.001[b]	0.40	--	0.013		A titanium stabilized alloy, more weldable than 430.
Sealing glass stainless steels															
Carpenter "27"	0.5[b]	28.0	Bal	--	0.05	0.60	0.40	--			--	--			Sealing glass material. No phase transformation till 1050oC
AL 430Ti		20.0	Bal												Modify 430 for sealing glass appl.
Carpenter "18"	--	18.0	Bal	--	0.10	0.60	0.40	--			0.40	--			Sealing glass composition with exactly TEC match

Co Base Alloys

Alloys[a]	Nominal composition, wt%															Characteristics, Typical applications
	Ni	Cr	Fe	Co	C	Mn	Si	Mo	W	Cb	Ti	Al	B	Zr	Others	
Haynes 6B (Stellite)	3.0	30.0	1.0	61.5	1.0	1.4	--	1.5	4.0	--	--	--	--	--	--	Solid solution alloy, as L-605, Haynes 188, s-186
Haynes 6K (Stellite)	2.0	31.0	3.0b	59.0	1.6	2.0b	2.0b	1.50b	4.50	--	--	--	--	--	--	Machine knives
UMCo-50	--	28.0	21.0	49.0	0.12[b]	--	--	--	--	--	--	--	--	--	--	Solid solution alloy
Haynes 150	3.0[b]	28	20.0	Bal	0.08	0.65	0.35	1.5[b]	--	--	--	--	--	--	--	Resistant thermal shock, high temperature corrosion (air & air-SO2)
ULTIMET	9	26	3	54	0.06	0.8	0.3	5.0	2.0	--	--	--	--	--	--	Appli. For severe corrosive attack env.
Haynes 188	22	22	3.0[b]	Bal	0.10	1.25[b]	0.3	--	14	--	--	--	--	--	0.04La	High strength and oxidation resistance >Hastelloy X; Aero-burner cans, after burner components

e. Some alloys are made by more than one manufacturer
f. Maximum composition
g. Cast alloy.

Cr-Base Alloys

Alloys[a]	Nominal composition, wt%															Characteristics, Typical applications
	Ni	Cr	Fe	Co	C	Mn	Si	Mo	W	Cb	Ti	Al	B	Zr	Others	
C207	--	Bal	--	--	0.10	--	--	--	7.5	--	0.2	--	--	0.8	0.15Y	Developed by GE
CI-41	--	Bal	--	--	0.09	--	--	7.1	--	--	--	--	--	--	0.2 (Y+La)	Developed by GE
IM-15	--	Bal	--	--	--	--	--	--	--	--	--	--	0.1	--	2.0 Ta 1.7 Ta 0.1 Y	Developed by NASA & Westinghouse
Chrome 30	--	Bal	--	--	--	--	--	--	--	--	0.5	--	--	--	6MgO	Bendix (Navy)
Chrome 90	--	Bal	--	--	--	--	0.5	--	--	--	--	--	--	--	3MgO, 2.5V	Bendix (Navy)
Chrome 90S	--	Bal	--	--	0.5	--	1.0	--	--	--	0.5	--	--	--	3MgO, 2.5Ta	Bendix (Navy)
Ducrolloy (Plansee)	--	Bal	5.0	--	--	--	--	--	--	--	--	--	--	--	1.0 Y_2O_3	Specifically developed for SOFC applications Made by PM approach

Alumina Forming Alloys

Alloys[a]	Nominal composition, wt%															Characteristics, Typical applications
	Ni	Cr	Fe	Co	C	Mn	Si	Mo	W	Cb	Ti	Al	B	Zr	Others	
	Ni-Cr-Fe Superalloys															
Nimonic 115	Bal	15.0	1.0[b]	14.0	0.16	1.0[b]	1.0[b]	4.0	--	--	4.0	5.0	0.002	0.15[b]	0.2[b]Cu	Turbine blades
IN MA-6000E	68.5	15.0	--	--	0.05	--	--	2.0	4.0	--	2.5	4.5	0.01	0.15	1.1 Y_2O_3, 2.0Ta	IN MA-6000E
Haynes 214[TM]	Bal	17.6	3.0	--	0.05	0.5	0.2	--	--	--	--	4.5	0.01	0.1	0.01Y	Developed for excellent Oxidation resistance
Astroloy[d]	Bal	15.0	--	15	0.06	--	--	525	--	--	3.5	4.4	0.03	--	--	Forgings at high temp.
Udimet 700	Bal	15.0	0.5[b]	18.5	0.07	0.2[b]	--	5.0	--	--	3.5	4.4	0.025	--	--	Jet engine parts
Rene 77[d]	Bal	15.0	1.0[b]	18.5	0.15[b]	--	--	5.2	--	--	3.5	4.25	0.05[b]	--	--	Jet engine parts
HAD 8077	Bal	16	--	--	--	--	--	--	--	--	--	4.0	--	--	--	ODS (Al_2O_3) alloy
Udimet 500	Bal	19.0	0.5[b]	18.0	0.08	--	--	4	--	--	3.0	3.0	0.007	--	--	Gas turbine parts/sheets/bolts
	Fe-Ni-Cr Superalloys															
Incoloy MA 956	0.50[b]	20	Bal	0.30[b]	0.10[b]	0.30[b]	--	--	--	--	0.5	4.5	--	--	0.5Y_2O_3	MAed ODS alloy, applications in turbine chambers or energy conversion

Alloys[a]	Nominal composition, wt%															Characteristics, Typical applications
	Ni	Cr	Fe	Co	C	Mn	Si	Mo	W	Cb	Ti	Al	B	Zr	Others	
	Ferritic Stainless Steels															
Kanthal (APM)	--	22	Bal	--	0.08	--	--	--	--	--	--	6.0	--	--	--	
Fecralloy	--	15.8	Bal.	--	0.03	--	---	--	--	--	--	4.8	--	--	0.3Y	
Armco 18 SR	0.25	18.0	Bal.	--	0.015	0.30	1.0	--	--	--	0.4	2.0	--		0.25N	
	Co Base Superalloys															
AiResist 215[c]	--	19	--	Bal	0.35	--	--	--	4.5	--	--	4.3	--	0.13	7.5Ta, 0.17Y	Nozzle vanes; resistant to hot corrosion
AiResist 13c	1.0[b]	21	2.5[b]	Bal	0.45	0.5[b]	--	--	11	2.0	--	3.5	--	--	0.1Y	High temperature parts
AiResist 213	--	19	--	Bal	0.18	--	--	--	4.7	--	--	3.5	--	0.15	6.5Ta, 0.1Y	Sheets, tubing; resistant to hot corrosion

Appendix C
Properties of Selected Alloys

I. Ni-Cr or Ni-Cr-Fe Base Alloys

Alloys	TEC $\times10^{-6}.K^{-1}$	Electrical resistivity (bulk) $\times10^{-6}\ \Omega.cm$	Yield strength $\sigma_{0.2}$ (bar) (MPa)	Elastic modulus (GPa)	Oxidation Resistance $\times10^{-6}\ mg^2.cm^{-4}.s^{-1}$	Corrosion resistance: Hot corr.=HCR Carbariz.=CR Stress corr.=SCR	Join-ability	Form-ability or Elongation.	Cost factor	Others Machinability (%) H resistance=HR Scaling resist.=SR
Inconel 671	15.0 20-800ºC	86.9	225 800ºC			Super, Esp. HCR		25%		
IN 657	~15.0 20-800ºC	~80-90			14.6 1,000ºC					
Inconel MA 758	15.0 20-760ºC	114	560 760ºC	228 RT		Exc. HCR		24%		
Nimonic 81	11.1 ~15.0 20-100-800ºC	127				Exc. HCR				
Haynes G-30	16.0 30-760ºC	116	202 538ºC	184 538ºC		Super esp. in phosp.	Readily	56%		16%
Inconel 690	16.5 20-760ºC	115	170 800ºC	211 RT		Exc. HCR	Readily	41%		
IN-587	~16-17 RT-800ºC	~100-120	663 760ºC			Exc. HCR		28%		
Haynes HR-160	16.6 RT-800ºC	112	215 760ºC	158 800ºC	>556, 800H	Exc. HCR, CR	Readily	68%		
NA-224	~16-17 RT-800ºC	~100-120				Exc. HCR			12	
Nicrofer 6025HT-602CA	16.6 RT-800ºC	118	220 ST 800ºC	154 800ºC		Excellent HCR good CR	Readily	30%		Good HR

Alloys	TEC $\times 10^{-6}.K^{-1}$	Electrical resistivity (bulk) $\times 10^{-6}\ \Omega.cm$	Yield strength $\sigma_{0.2}$ (bar) (MPa)	Elastic modulus (GPa)	Oxidation Resistance $\times 10^{-6}\ mg^{2}.cm^{-4}.s^{-1}$	Corrosion resistance: Hot corr.=HCR Carbariz.=CR Stress corr.=SCR	Join-ability	Form-ability or Elongation	Cost factor	Others Machinability (%) H resistance=HR Scaling resist.=SR
Nimonic 86	~15-16 RT-800°C	~100-120				Exc. HCR		41%		20%
RA-333	~17-18 RT-800°C	~100-120				Excellent HCR			5.1	
IN-597	~16-17 RT-800°C	~100-120	663 760°C					15%		
Nimonic 101	~16-17 RT-800°C	~100-120		129 800°C		Low in NaCl env<N.80A,90		Good		10%
Inconel 601	16.5 27-760°C	119	200 SP 760°C	155 760°C	12.2 1,000°C	Good HCR Good CR	Readily	45% in 2in Exc.	4.0	20% Exc. SR.
Hastelloy C-2000	14.0 20-700°C	128		372 RT	Exc. both ox & re env	Exc. HCR, CR in Both ox & re env	Readily	63%		
IN-939	14.0 20-800°C	123	690 760°C	150 800°C		Exc.		3.5%		
Haynes 230	15.2 25-800°C	125	285 760°C	164 800°C	5.5 2.2 1,100 1,000°C	Exc. HCR Good CR	Readily	48%		Moderate MB as all solution alloys
Inconel 617	11.6 20-100°C	122	350 RT	211 RT		Good HCR	Readily	58%		
Hastelloy G	16.4 21-650°C	~100-120	220 s 760°C	160 145°C		Good HCR Exc. CR	Readily	50%		18%
Hastelloy G-3	14.6 20-100°C	~100-120	320 RT	199 RT		Exc. in intergranular CR	Readily	50%		18%
Hastelloy X	16 26-816°C	118	262 s 760°C	196 RT	69.4 1,100°C	Good HCR Good SCR	Readily	12.3 mm O 43%	5.2	18%
Hastelloy HX	16.1 26-816°C	116	261 760°C	143 800°C		Good	Readily	45.5%		18%
Pyromet 680	16.0 26-816°C	118	241 760°C	144 816°C		Good HCR Good SCR	Readily	50.0		

Alloys	TEC $\times 10^{-6}.K^{-1}$	Electrical resistivity (bulk) $\times 10^{-6}\,\Omega.cm$	Yield strength $\sigma_{0.2}$ (bar) (MPa)	Elastic modulus (GPa)	Oxidation Resistance $\times 10^{-6}\,mg^{2}.cm^{-4}.s^{-1}$	Corrosion resistance: Hot corr.=HCR Carbariz.=CR Stress corr.=SCR	Join-ability	Form-ability or Elongation	Cost factor	Others Machinability (%) H resistance=HR Scaling resist.=SR
Hastelloy C-22	15.3 21-760°C	114	269 s 760°C	163 760°C		Exc. HCR, SCR	Superior	62%		20%
Inconel 625	15.3 21-760°C	128	421 760°C	160 760°C	69.4 1,100°C	Exc. HCR and SCR	Readily	50%		16-18%
Inconel 622	14.1 21-982°C	122	210 760°C	200 760°C		Exc. HCR, SCR Ox & re env.	Readily	62%		Structure & prop. Stable with temp.
Inconel 686	12.0 ~16.5 20-100-800°C	123.7	245 s 530°C			Exc.	Readily	60%		Exc. HR
Inconel 725™	13.0 ~17.0 20-100-800°C	114.4	500 760°C			Exc. HCR		35%		
Hastelloy G-50	13.0~17.0 26-93-800°C	~100-120	993 RT	192 RT		Good HCR	Readily	19%		
Hastelloy D-205 ™	~16~17.0 RT-800°C	~100-120	337 RT			Exc. HCR, SCR in acidic media	Readily	56.5%		Silica forming alloy
Nimonic 263 RollsRoyce263	15.4 20-800°C	115	515 760°C	166 800°C		Good HCR	Readily	Exc.		16%
IN-853	~16-17 RT-800°C	~100-120	559 760°C					9%		16%
Inconel MA 754	12.2 26-93°C	108	400 760°C			Exc.	Readily	20%		
Inconel 050										
TDNiC	~15 26-93-800°C	~100-120	262 s 760°C				Readily	20%		
Nimonic 75	16.2 20-760°C	119	185 760°C			Good	Readily	41%		
Nimonic 95	~15 RT-800°C	~100-120	1100 760°C				Readily	15%		6%

Alloys	TEC $\times 10^{-6}.K^{-1}$	Electrical resistivity (bulk) $\times 10^{-6}\ \Omega.cm$	Yield strength $\sigma_{0.2}$ (bar) (MPa)	Elastic modulus (GPa)	Oxidation Resistance $\times 10^{-6}\ mg^2.cm^{-4}.s^{-1}$	Corrosion resistance: Hot corr.=HCR Carbariz.=CR Stress corr.=SCR	Join-ability	Form-ability or Elongation	Cost factor	Others Machinability (%) H resistance=HR Scaling resist.=SR
Nimonic 90 (pyromet 90)	16.2 20-760°C	114	538 760°C	214 RT		Good in NaCl > N.101, 91	Readily	23%		10%
Waspaloy A[d]	15.4 20-800°C	124	676 760°C	164 800°C	16 1000°C	Good	Readily	25%		14%
Waspaloy B[d]	Close to Waspaloy A, except no addition of 0.02S and 0.1 Cu for improved machinability.									
Nimonic 80	12.7 20-100°C	124	660 760°C		Good	Good HCR	Readily	38%		Close to N.75, ex. more Al and Ti
Nimonic 80A	16.5 20-800°C	117	504 760°C			Good in NaCl > N.101, 91	Readily	24%		18%
Udimet 520	~15 25-800°C	~100-120	725 760°C					21%		
Haynes R-41	15.2 20-800°C	130.8	752 760°C	169 800°C	6.5 1000°C	Good HCR	Less Readily	16.6%		
Pyromet M-252, (carpenter)	14.0 20-816°C	~100-120	718 760°C	156 760°C	Exc. Up to 982°C	Good HCR	Readily	25%		<10% (difficult)
Inconel 718	16.0 21-760°C	121 aged 127 annealed	739 760°C	154 760°C	40 1,100°C	Good HCR	Readily PT &ST	21%		14-16%
Udimet 710	~15-16 RT-800°C	~100-120	829 760°C					17%		
Udimet 720	~15-16 RT-800°C	~100-120	814 760°C					7%		
Nimonic PK 33	12.1 20-100°C	126	620 800°C			Good HCR	Readily	33%		

II. Fe-Ni-Cr Base Alloys

Alloys	TEC RT~800°C $\times10^{-6}.K^{-1}$	Electrical resistivity (bulk) $\times10^{-6}\,\Omega.cm$	Yield strength $\sigma_{0.2}$ (MPa)	Elastic Modulus (GPa)	Oxidation Resistance $\times10^{-6}\,mg^{2}.cm^{-4}.s^{-1}$	Corrosion resistance: Hot corr.=HCR Carbariz.=CR Stress cor.=SCR	Join-ability	Form-ability or Elongation	Cost factor	Others Machinability (%) H resistance=HR Scaling resist.=SR
Incoloy 028	16.7 20-426°C	99	214 RT	200 RT		Exc. in both Oxi. & red. Env.		40%		
Incoloy 803	17.1 21-649°C	103	215 760°C	195 RT		Exc. HCR, CR Good SCR		46%		Exc. resist. To cyclic oxidation
Haynes HR-120	17.3 26-800°C	105	375 s RT	197 RT		Exc. HCR, CR Good SCR	Readily	50% s	3.5	
20Mo-6	16.87 26-800°C	108	275 RT	186 RT		Exc. HCR, CR Good SCR	Readily	50%		
20Mo-4	16.87 26-800°C	106	262 RT	186 RT		Good SCR	Readily	41%		
Pyromet 31 (carpenter)	16.1 21-816°C	122	669 760°C	154 816°C		Exc. HCR, SCR	Readily	41%		
Incoloy 864	16.4 21-649°C	104	140 760°C	195 RT			Readily	41%		For exhaust gas re-circulation tubes
Incoloy 556™	16.7 26-800°C	95.2	220 760°C	148 800°C		Exc. HCR, CR Good SCR	Readily	47.7%	8.5	
Incoloy 825	17.1 26-760°C	113	183 760°C	206 RT	3.3 1,000°C.	Exc. HCR, CR Good SCR	Readily	45%		
Aktiebolag 253 MA	19.0 26-760°C	84	110 760°C	115 760°C	< alloy 601	Good.	Readily	51%	2.3	
Incoloy 800	14.4 20-100°C	99	213 550°C	193 RT	2.7 1,000°C	Exc. HCR, CR Good SCR	Readily	44%		16% SR.<that of 310 (poor)
Incoloy 925	13.2 25-93°C	116	640 ps 639°C		Exc. both reduc. & oxid.	Exc. HCR, CR Good SCR	Readily	24%		
N-155, Multimet alloy	17.5 26-800°C	93	393 RT	214 RT		Good	Readily	43%		16-20%
Incoloy 802	~16-18 RT-800°C	~100-120								

Alloys	TEC RT~800°C $\times10^{-6}.K^{-1}$	Electrical resistivity (bulk) $\times10^{-6}\,\Omega.cm$	Yield strength $\sigma_{0.2}$ (MPa)	Elastic Modulus (GPa)	Oxidation Resistance $\times10^{-6}\,mg^2.cm^{-4}.s^{-1}$	Corrosion resistance: Hot corr.=HCR Carbariz.=CR Stress cor.=SCR	Join-ability	Form-ability or Elongation	Cost factor	Others Machinability (%) H resistance=HR Scaling resist.=SR
S-590	~16-18 RT-800°C	~100-120								
Incoloy 801	~16-18 RT-800°C	~101.2	197 RT	207 RT	Same as 801	Same as 801		53%		20%
Incoloy 840	Low Ni alloy developed for the manufacture of the seam-welded tubing used for the sheathing of electrical resistance heating elements.									
Armco 20-45-5	~16-18 RT-800°C	~100-120								
Incology 25-6 Mo	16.9 21-649°C	80	170 760°C	188 RT		Exc. in natural & acidic env.		42%		6.5% Si may be too high for SOFC
Incoloy 020	16.8 20-100°C	108	160 760°C			Exc. HCR, CR Good SCR		41%		
19-9DX	Close to 19-9DL									
19-9DL	18.0 20-816°C	77	138 816°C		Exc. upto 677°C	Exc. upto 677°C	Readily	39%		
RA-330	18.0 20-760°C	101.7	140 760°C	117 760°C		Exc. HCR, CR Good SCR		45%	2.8	Cycl. oxid. resis. Not good
RA-330 HC	Close to RA330									
Rolled Alloys RA85H	~16-18 RT-800°C	~100-120				Exc. CR				
Incoloy DS	15.0 20-100°C	108	140 760°C			Exc. CR		60%		Exc. internal oxidation resist.

III. Ferritic Stainless Steels

Alloys	TEC RT~800°C $\times 10^{-6}.K^{-1}$	Electrical Resistivity (bulk) $\times 10^{-6}\,\Omega.cm$	Yield strength $\sigma_{0.2}$ (MPa)	Elastic Modulus (GPa)	Oxidation Resistance $\times 10^{-6}$ $mg^2.cm^{-4}.s^{-1}$	Corrosion resistance: Hot corr.=HCR Stress cor.=SCR Carbariz.=CR	Join-ability	Form-ability or Elongation	Cost factor	Others Scaling resist.=SR Machinability (%) H resistance=HR
29-4-2 (AL)	9.4 20-100°C	~60-80	655 605 RT 400°C	207 RT		Exc. Comp. to supera	Fairly	25%		Exc. SR
29-4C (AL)	10.4 RT-400°C	~60-80	500 RT	207 RT	Exc. >E-Bite, 446 at 800°C	Exc. HCR, SCR	Fairly	>20%		Exc. SR
7-Mo Stainless (Carpenter)	13.3 14.7 25-538-760°C	77.5	565 RT	200 RT		Exc. HCR, SCR	Readily	31%		
Alloy 255 (AL)	13.8 25-500°C	82.1	>480 RT			Exc. HCR, SCR	Readily	>20%		
E-Brite 26-1	9.9 11.8 20-100-500°C	~60-80	>275 RT		5.4 1,000°C	Exc. <29-4-2	Fairly	30%		Good SR
Sea-cure/Sc-1	~13 RT-800°C	~60-80	>380 RT			Exc. HCR, SCR	Fairly	>20%		
Monit	~13-14 RT-800°C	~60-80	>550 RT			Exc. HCR, SCR	Readily	>20%		
26-1 Ti	~12-13 RT-800°C	~60-80	>275 RT			Exc. HCR, SCR	Fairly	>20%		
18-2FM	~12 RT-800°C	~60-80				Exc. HCR, SCR	Fairly			
446	10.4 11.2 20-100-538°C	67	>275 <55* RT 760°C	200 RT	2.6 1,000°C	Exc.	Fairly	>20%	1	Good SR * tensile strength
AL 453™	11.4 12.3 RT-538-816°C	73.3	310 39 RT 760°C	200 RT (est.)	0.22 760°C	Exc. HCR, SCR	Fairly	35%	1	Exc. SR
Carpenter 443	12.1 20-649°C	68	>275 RT	200 RT		Good	Fairly	>20%		Good SR

Ferritic stainless steels (cont.)

Alloys	TEC RT~800°C $\times10^{-6}.K^{-1}$	Electrical Resistivity (bulk) $\times10^{-6}\,\Omega.cm$	Yield strength $\sigma_{0.2}$ (MPa)	Elastic Modulus (GPa)	Oxidation Resistance $\times10^{-6}$ $mg^2.cm^{-4}.s^{-1}$	Corrosion resistance: Hot corr.=HCR Stress cor.=SCR Carbariz.=CR	Join-ability	Form-ability or Elongation	Cost factor	Others Scaling resist.=SR Machinability (%) H resistance=HR
AL 433™	11.80 RT-650°C	65	325 RT, 80 760°C	200 RT	0.10 815°C	Good		32%		
Carpenter 443	12.10 RT-650°C	~ 60-70	345 RT, 41 760°C	200 RT		Good		22%		
AL 468™	12.50 RT-800°C	63	282 RT, 62.0 760°C	200 RT	0.17 815°C	Good		33%		
AL 441 HP™	11.3 RT-800°C	58.7	290 RT, 57.8 760°C	200 RT	0.10 815°C	Good	Fairly	31.0%		
AL 439 HP™	12.50 RT-800°C	63	310 RT, 48.8 760°C	200 RT	0.20 815°C	Good.	Fairly	34%		Good SR
Sealing-glass alloys										
AL 430Ti										
Carpenter "18"	9.9 11.3 RT-200-500°C	60	310 RT	200 RT		Good		25%		Exactly TEC match with glass
Carpenter "27"	10.0 11.0 RT-200-500°C	63	345 RT	207 RT		Good		25%		Exactly TEC match with glass

VI. Co-Base Alloys

Alloys	TEC RT~800°C $\times10^{-6}.K^{-1}$	Electrical resistivity (bulk) $\times10^{-6}\,\Omega.cm$	Yield strength $\sigma_{0.2}$ (MPa)	Elastic Modulus (GPa)	Oxidation Resistance $\times10^{-6}\,mg^2.cm^{-4}.s^{-1}$	Hot Corrosion resistance	Join-ability	Form-ability or Elongation	Cost factor	Others Machinability (%) H resistance=HR Scaling resist.=SR
Haynes 6B (Stellite)	16.3 0-800°C	91.0	260 860°C			Exc. SCR, HCR	Readily	17%		
Haynes 6K (Stellite)	14.5 0-800°C	~60-90	310 815°C			Exc. SCR, HCR		4%		
UMCo-50	16.8 20-1000°C	82.5	150 700°C	215 RT		Exc. SCR, HCR	Readily	8%		
Haynes 150	16.9 25-760°C	87	275 538°C	180 649°C		Exc. SCR, HCR	Exc.	38%		Welding mater.
Haynes 188	16.5 20-800°C	101	290 s 760°C	169 s 800°C	Close 230 >X,617,625	Excellent HCR >230	Readily	56%		12-14%

V. Cr-Base Alloys

Alloys	TEC RT~800°C $\times 10^{-6}.K^{-1}$	Electrical resistivity (bulk) $\times 10^{-6}\ \Omega.cm$	Yield strength $\sigma_{0.2}$ (MPa)	Elastic Modulus (GPa)	Oxidation Resistance $\times 10^{-6}\ mg^2.cm^{-4}.s^{-1}$	Hot Corrosion resistance	Join-ability	Form-ability or Elongation	Cost factor	Others Machinability (%) H resistance=HR Scaling resist.=SR
C207										
CI-41										
IM-15										
Chrome 30										
Chrome 90										
Chrome 90S										
Ducrolloy (Plansee)	11.8 20-1000°C				4.60 1,000°C	Exc. HCR, SCR		<10%		

VI. Alumina Forming Alloys

Alloys	TEC RT~800°C $\times 10^{-6}.K^{-1}$	Electrical resistivity (bulk) $\times 10^{-6}\,\Omega$.cm	Yield strength $\sigma_{0.2}$ (MPa)	Elastic Modulus (GPa)	Oxidation Resistance $\times 10^{-6}$ $mg^2.cm^{-4}.s^{-1}$	Hot Corrosion resistance	Join-ability	Form-ability or Elongation	Cost factor	Others Machinability (%) H resistance=HR Scaling resist.=SR
VI. Ni base superalloys										
Nimonic 105	~16-18 20-800°C	~120-140				Excl. SCR, HCR	Readily			Good SR, HR
Haynes 214™	16.6 20-800°C	134	640.5 760°C	162 800°C	Super >> alloy 230	Super. SCR, HCR	Readily	36.8%		18% Good SR, HR
IN MA-6000E	~16-18 20-800°C	~120-140				Excl. SCR, HCR	Readily			Good SR, HR
Astroloy[d]	~16-18 20-800°C	~120-140			13 1,000°C	Excl. SCR, HCR	Readily			Good SR, HR
Udimet 700	~16-18 20-800°C	~120-140				Excl. SCR, HCR	Readily			12% Good SR, HR
Rene 77[d]	~16-18 20-800°C	~120-140				Good. SCR, HCR	Readily			Good SR, HR
HAD 8077	~16-18 20-800°C	~120-140				Good. SCR, HCR	Readily			Good SR, HR
Udimet 500	13.3 20-100°C	120.3	731 760°C			Good HCR	Readily	32%		12% Good SR, HR
Fe base superalloys										
MA956	11.3 20-100°C	131	120 800°C			Super. SCR, HCR		9%		Exc. SR, HR

Alloys	TEC RT~800^{o}C $\times 10^{-6}.K^{-1}$	Electrical resistivity (bulk) $\times 10^{-6}\ \Omega.cm$	Yield strength $\sigma_{0.2}$ (MPa)	Elastic Modulus (GPa)	Oxidation Resistance $\times 10^{-6}\ mg^2.cm^{-4}.s^{-1}$	Hot Corrosion resistance	Join-ability	Form-ability or Elongation	Cost factor	Others Machinability (%) H resistance=HR Scaling resist.=SR
Co base superalloys										
AiResist 215c										
AiResist 213										
AiResist 13[c]										4%
VII. Ferritic Stainless Steels										
Kanthal (APM)	16.3 20-1000^{o}C	~120-140			1.0 1,000^{o}C	Super. SCR, HCR				Exc. SR
Fecralloy	11.1 12.2* 20-100 650^{o}C	134	>550 <100 RT 800^{o}C	200 (est)				<25%		Exc. SR

* Tested at PNNL

VI.Selected Elemental Metals and Intermetallics

Alloys	TEC RT~800°C $\times 10^{-6}.K^{-1}$	Electrical resistivity (bulk) $\times 10^{-6}\ \Omega.cm$	Yield strength $\sigma_{0.2}$ (MPa)	Vapor pressure (Pa)	Elastic Modulus (GPa)	Oxidation Resistance $\times 10^{-6}\ mg^2.cm^{-4}.s^{-1}$	Melting point (°C)	Join-ability	Form-ability or Ductility	Cost factor	Others H resistance Scale adherence machinability
Silver FCC	20.61 0-500°C	1.7	55 RT	10^{-2} 800°C	71 RT		961				
Gold FCC	14.2 20°C	2.4	125 RT		74.5 RT		1064		30%		
Platinum FCC	9.1 20-100°C	10.6	150 RT	10^{-22} 800°C	156 RT		1769		35%		
Nickel FCC	13.3 18.9 20-100~1000°C	6.8	>150 RT		207 RT		1433				
Copper FCC	16.5 23.0 20 800°C	10		1.3×10^{-3} 946°C	68 <100>		1084				
Chromium BCC	6.2 RT	130	282 RT	10^{-4} 965°C	248		1875				
Aluminum FCC	23.6 20~100°C	26.5	10~35 (annealed)		62		660				
Titanium HCP	8.4 10.1 20 1000°C	420	140	10^{-5} 800°C			1875				
Fe_3Al Ordered BCC					141		1540				
Ni_3Al Ordered FCC	12.3 15.6 20 800°C		500 (est) 800°C		178	Limited >650°C	1390				

Notes:

1. Yield strength $\sigma_{0.2}$ (bar) (MPa): yield strength at 0.2% offset. Normally data from bar tests at a temperature around 800^{o}C is collected. If bar test data is not available, the sheet test data is used and marked as B in tables. Typically a yield strength from a bar test is higher that that from a sheet test.
2. Oxidation resistance is measured by the parabolic rate constant in unit of $mg^2. cm^{-4}.s^{-1}$
3. Corrosion resistance: including hot corrosion (sulfidation) and carburization resistance, abbreviated as HCR and CR respectively.
4. Formability: measured by Erichsen or Olsen cupping depth (mm), marked as E and O, respectively. If the E or O cupping depth at room temperature (RT) is not available, the elongation data from bar tests is colleted as alternatives for comparison. The data from sheet tests will be used and marked as S in case bar test data is not available.
5. The (bulk) electrical resistance at room temperature is used here. The resistance usually increases with temperature, but normally the resistance (increasing) coefficient is small. The resistance at room temperature provides enough information for evaluation of electrical resistance of alloys.
6. Cost factor is the ratio of ($/lb of alloy) /($/lb of stainless steel 446) in ¼" mils sheet.
7. Machinability of alloys is expressed as a percentage by referring Seco Tools AB. Decreasing values indicate increasing machining difficulty.

Abbreviations:

RT: room temperature
ST: solution treated;
PT: precipitation treated;
SP: solution + precipitation treated;
OCD: typical Olsen cup depth;
SSS: stainless steel;
"~": Estimated by authors.