**Heat and corrosion resistant alloys for chemical processing systems**

Regular advancement in metallurgical and fabrication procedures had led to the development of broad range of nickel alloys and their extensive use in the chemical industrial sector.

The nickel alloys render with outstanding corrosion resistance, strength, hardness, metallurgical stability, fabrication and welding properties. Most of nickel alloys also offer excellent heat resistance that makes them a supreme choice for applications that need chemical resistance and durability at the high temperatures.

The study of wrought nickel based alloys includes various wrought corrosion resistance alloys that are extensively utilized in the chemical units. The chemistries and UNS system of the popular nickel based alloys are described in the following table:

**Chemical composition of popularly industrially used Nickel based super alloys**

| Alloy | UNS | Nickel | Chromium | Molybdenum | Iron | Tungsten | Copper | Others |
|---|---|---|---|---|---|---|---|---|
| Nickel 200 | N02200 | 99.6 % | - | - | - | - | - | - |
| Monel 400 | N04400 | 66.5 % | - | - | 1 % | - | 31.5 % | Mn 1 |
| Inconel 600 | N06600 | 75 % | 15.5 % | - | 8 % | - | - | - |
| Inconel 625 | N06625 | 62 % | 21.5 % | 9 % | 2.5 % | - | - | (Nb + Ta) 3.8 |
| Inconel 690 | N06690 | 61 % | 29 % | - | 9 % | - | - | - |
| Incoloy 825 | N08825 | 42 % | 21.5 % | 3 % | 29.5 % | - | 2.3 % | Ti 1 |
| Hastelloy G-3 | N06985 | 44 % | 22 % | 7 % | 19.5 % | 1.5 % | 2 % | Nb 2.1 |
| Hastelloy G30 | N06030 | 43 % | 29.8 % | 5 % | 15 % | 2.8 % | 1.7 % | Nb + Ta 1 |
| Hastelloy C276 | N10276 | 57 % | 15.5 % | 16 % | 5.5 % | 3.8 % | - | - |
| Hastelloy C22 | N06022 | 56 % | 22 % | 13 % | 3 % | 3 % | - | - |
| Hastelloy C2000 | N10200 | 59 % | 23 % | 16 % | 1.5 % | - | 1.6 % | - |
| Inconel 622 | N06022 | 58 % | 20.5 % | 14.2 % | 2.3 % | 3.2 % | - | - |
| Inconel 686 | N06686 | 60 % | 21 % | 16 % | 5 % | 3.7 % | - | - |
| Alloy 59 | N06059 | 60 % | 23 % | 15.8 % | 1.5 % | - | 1.6 % | - |
| Hastelloy B2 | N10665 | 69 % | 1.0 % | 28 % | 2 % | - | - | - |
| Hastelloy B3 | N10675 | 68.5 % | 1.5 % | 28.5 % | 1.5 % | 3 % | - | - |
| Hastelloy B-4 | N10675 | 68.5 % | 1.5 % | 28.5 % | 1.5 % | 3 % | - | - |

**Characteristics**

Nickel alloys are costlier than stainless steel grades. Although considering the long term economical benefit, steels are costlier because of their higher maintenance cost required after a specific length of time. For example Nickel-Chromium-Molybdenum alloys are costlier by 5 times than 18Chromium-8Nickel stainless steels and 2 times more than super austenitic stainless steels. The Nickel based alloys have similar thermal expansion values as of carbon steel however much lower than stainless steel 300 series.

The thermal conductivity of pure nickel is better than carbon steel, but most of nickel alloys offer small values of conductivity, in few conditions even much smaller than austenitic stainless steel grades.

Excluding the pure nickel, the nickel alloys utilized in chemical processing are a stronger material than Stainless steel 300 series. Ni alloys offers excellent ductility and hardness as shown in the following table. Highest design stresses for many alloys shown in the following table are used in the chemical processing systems as stated in Section 8 of ASME Boiler and Pressure Vessel Code.

<u>Mechanical characteristics</u>

| Alloys | Ultimate tensile strength | Yield strength, ksi | Elongation, % |
|---|---|---|---|
| Nickel 200 | 55 ksi | 15 ksi | 40 % |
| Monel 400 | 70 ksi | 28 ksi | 35 % |
| Inconel 600 | 80 ksi | 35 ksi | 30 % |
| Inconel 625 | 110 ksi | 55 ksi | 30 % |
| Inconel 690 | 85 ksi | 35 ksi | 30 % |
| Incoloy 825 | 85 ksi | 35 ksi | 30 % |
| Hastelloy G-3 | 90 ksi | 35 ksi | 45 % |
| Hastelloy G30 | 85 ksi | 35 ksi | 30 % |
| Hastelloy C276 | 100 ksi | 41 ksi | 40 % |
| Hastelloy C22 | 100 ksi | 45 ksi | 45 % |
| Hastelloy C2000 | 100 ksi | 45 ksi | 45 % |
| Inconel 622 | 110 ksi | 51 ksi | 45 % |
| Alloy 59 | 110 ksi | 51 ksi | 40 % |
| Hastelloy B2 | 110 ksi | 51 ksi | 40 % |
| Hastelloy B3 | 110 ksi | 51 ksi | 40 % |
| Hastelloy B-4 | 110 ksi | 51 ksi | 40 % |

The nickel alloys exhibit completely austenitic microstructures. Almost all grades used in the chemical plants are solid solution strengthened alloys. They receive better strength characteristics from the inclusion of suitable hardeners for instance, molybdenum and tungsten, instead from the carbide preparation. Similar to austenitic stainless steels, solid solution nickel alloys cannot be reinforced by heat processing, solely through cold processing.

Second main category of nickel based alloys is reinforced by precipitation hardening heat processing. These are widely taken for ultrahigh strength based applications for example in deep oil or gas production and extensively high pressure procedures.

Excluding the chosen parts in valves and rotating machinery, precipitation hardened nickel alloys have only a few applications in the chemical industry. This class of alloys called as heat resistant super alloys that are used in gas turbines, combustion chambers and aerospace applications.

## Corrosion resistance

Nickel alloys describe an advanced form from the traditional austenitic stainless steels and super austenitic iron based alloys in preventing attack in the extensive range of acids, alkalis and salts. The excellent feature of nickel based super alloys is outstanding resistance in aqueous solution media containing halide ions. Considering this, nickel alloys are much better than austenitic stainless steels as they are reluctant to be attacked by wet chlorides and fluorides.

The excellent corrosion resistance nature of nickel alloys not only decreases the material loss, even also it has the ability to better prevent the localized corrosion, pitting and crevice corrosion, intergranular corrosion and stress corrosion cracking. These kinds of localized corrosion, much more than natural loss are considered as the major material loss factors in the chemical processing plants.

The Nickel based alloys attribute corrosion resistance properties due to lower reactivity of nickel as compare to iron as evidenced from its nobler oxidation potential in EMS series. Comparable to stainless steels, chromium containing nickel based alloys passivate easily. The additional benefit of nickel rather iron is the capability to get combined with variety of composition elements without causing the production of brittle phases. The common combining elements are molybdenum, chromium and copper.

Relative resistance ratings of nickel based alloys in the general chemical unit conditions

| Alloy | Sulfuric acid ($H_2SO_4$) | Phosphoric acid ($H_3PO_4$) | Hydrochloric acid (HCl) | Hydrofluoric acid (HF) | Nitric acid ($HNO_3$) | Organic acids | Strong alkalis | Reducing salts | Oxidizing salts |
|---|---|---|---|---|---|---|---|---|---|
| Nickel 200 | Good to acceptable | Good to acceptable | Good to acceptable | Excellent to good | Bad response | Excellent to good | Excellent to good | Excellent to good | Bad response |
| Monel 400 | Excellent to good | Good to acceptable | Good to acceptable | Excellent to good | Bad response | Excellent to good | Excellent to good | Excellent to good | Bad response |
| Inconel | Good to | Good to | Bad | Good to | Good to | Excellent | Excellent | Excellent | Good to |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 600 | acceptable | acceptable | response | acceptable | acceptable | to good | to good | to good | acceptable |
| Inconel 625 | Excellent to good | Excellent to good | Excellent to good | Excellent to good | Excellent to good | Excellent to good | Excellent to good | Excellent to good | Excellent to good |
| Inconel 690 | Good to acceptable | Excellent to good | Good to acceptable | Excellent to good | Excellent to good | Excellent to good | Excellent to good | Excellent to good | Excellent to good |
| Incoloy 825 | Excellent to good | Excellent to good | Good to acceptable | Bad response | Excellent to good | Excellent to good | Good to acceptable | Excellent to good | Good to acceptable |
| Hastelloy G-3 | Excellent to good | Excellent to good | Good to acceptable | Excellent to good | Excellent to good | Excellent to good | Excellent to good | Excellent to good | Excellent to good |
| Hastelloy C-276 | Excellent to good | Excellent to good | Good to acceptable | Excellent to good | Good to acceptable | Excellent to good | Excellent to good | Excellent to good | Excellent to good |
| Hastelloy B-2 | Excellent to good | Excellent to good | Excellent to good | Excellent to good | Bad response | Excellent to good | Excellent to good | Excellent to good | Bad response |

The above instructions are not aimed for specification functions but just as a starting factor in the selection of a material.

**Welding instructions**

Most of the nickel alloy's welding is done by shielded  metal arc welding (SMAW), gas tungsten arc welding (GTAW) and gas metal arc welding (GMAW). The Nickel alloy weldments are extremely ductile and their small thermal expansion values decrease residual stress and warpage. The post weld heat processing is normally needed solely for precipitation hardenable grades. The specifications released by American Welding Society (AWS) for nickel alloy welding electrodes and filler metals are shown in the following table:

| Alloy | Welding electrode (A5.11) | Filler metal (A5.14) |
|---|---|---|
| Nickel 200 | ENi-1 | ENi-1 |
| Monel 400 | ENiCu7 | ENiCu7 |
| Inconel 600 | ENiCrFe-3 | ENiCrFe-3 |
| Inconel 625 | ENiCrMo-3 | ENiCrMo-3 |
| Hastelloy G-3 | ENiCrMo-9 | ENiCrMo-9 |
| Hastelloy G-30 | ENiCrMo-11 | ENiCrMo-11 |
| Hastelloy C276 | ENiCrMo-4 | ENiCrMo-4 |
| Hastelloy C22 | ENiCrMo-10 | ENiCrMo-10 |
| Inconel 622 | ENiCrMo-10 | ENiCrMo-10 |
| Inconel 686 | ENiCrMo-14 | ENiCrMo-14 |

| | | |
|---|---|---|
| Alloy 59 | ENiCrMo-13 | ENiCrMo-13 |

The welding procedures for nickel alloys are much similar to austenitic stainless steels. Although because of higher sluggishness of Nickel based weld puddles and the smaller penetration properties of nickel alloys, the formation of complete penetration welds may need modification of joint structure and welding methods. The Nickel alloys are less tolerant as compare to ferrous alloys to contaminants that may result in weld embrittlement.

The properties like good ductility, low thermal expansion and potential to withstand dilution by several metallic elements have made nickel based welding consumables globally proven for welding with various metals. It not just involves the nickel based alloys welding to iron based alloys, in fact also welding of stainless steels to carbon and alloy steel grades. Similarly the nickel based alloys can be weld accumulated on carbon steel without posing the threat of fracturing.

**Nickel Alloy Types**

The nickel alloys are made in the commercial product forms such as plate, sheet, wire, strip, tubes, pipe, fittings and forgings. Chosen ASTM specifications of few of these forms are shown in the following table:

| Alloy | Plate or Sheet | Seamless Pipe | Welded pipe | Seamless tubes | Welded tubes |
|---|---|---|---|---|---|
| Nickel 200 | B162 | B161 | B725 | B161 | B730 |
| Monel 400 | B127 | B165 | B725 | B165 | B730 |
| Inconel 600 | B168 | B167 | B517 | B167 | B516 |
| Inconel 625 | B443 | B444 | B705 | B444 | B704 |
| Inconel 690 | B168 | B167 | | B167 | |
| Incoloy 825 | B409 | B407 | | B407 | B515 |
| Hastelloy G-3 | B582 | B622 | B619 | B622 | B626 |
| Hastelloy G-30 | B582 | B622 | B619 | B622 | B626 |
| Hastelloy C-276 | B575 | B622 | B619 | B622 | B626 |
| Hastelloy C-22 | B575 | B622 | B619 | B622 | B626 |
| Hastelloy C-2000 | B575 | B622 | B619 | B622 | B626 |
| Inconel 622 | B575 | B622 | B619 | B622 | B626 |
| Inconel 686 | B575 | B622 | B619 | B622 | B626 |
| Alloy 59 | B575 | B622 | B619 | B622 | B626 |
| Hastelloy B-2 | B333 | B622 | B366 | B622 | B626 |

Some nickel alloys are also made as castings. These normally offer various properties from their wrought counterparts.

Nickel alloys are generally categorized to their principal alloying agents. The family of nickel alloys widely used in the chemical plant system is generally featured as:

**Pure Nickel**-Pure nickel or grade 200 offers exceptional resistance to an extensive range of reducing acids and salts however it is not recommended for use in the strong oxidizing media for example nitric acid. The most crucial feature of pure nickel is outstanding resistance to caustic alkalis even also in the molten state. However excellent in its resistance to arid halogen conditions, Nickel is not suitable resistant at lower than water dewpoint. For applications above 600oF, a low carbon grade alloy 201 is a recommended material.

Nickel-Copper Alloy 400: The corrosion functionality of alloy 400, as that of nickel is excellent in the reducing conditions and can be affected by aeration and oxidizing media. Monel 400 exhibits excellent resistance to halogen acids and compounds specifically hydro-fluoric acid and hot gases rich in fluorine or hydrogen fluoride. The alloy is extensively used for handling sulfuric acid solutions, marine water and brines. For applications demanding greater strength for example valve and pump parts, alloy K-500 is used that is a precipitation hardenable version of 400 Monel.

**Nickel-Chromium-Iron alloy 600**: the inclusion of chromium to nickel configuration increases the suitability of alloy 600 in the oxidizing media. However only moderate for mineral acids, 600 alloy offers outstanding resistance to organic acids and is widely utilized in fatty acid processing. It is also widely used in the formation and handling of caustic and alkali chemicals. Inconel alloy 600 is also a best material for use in the elevated temperature applications that demand heat and corrosion resistance. Its exceptional functionality in the warm halogen conditions makes it a suitable choice for organic chlorination procedures. Other high temperature degradation procedures where alloy 600 has shown outstanding resistance are oxidation, carburization and nitridation.

Nickel-Chromium-Molybdenum Alloy 625: The addition of molybdenum to Nickel-Chromium matrix extends prevention to attack in mineral acids and salts of oxidizing and reducing nature. Molybdenum further increases resistance to pitting and crevice attack by wet chlorides. Alloy 625 is a high strength super alloy with outstanding fatigue strength. Similar to grade 600, alloy 625 is also a heat and corrosion resistant material. The mixture of outstanding high temperature strength and resistance to corrosion by oxidation, halogens and carburization, make alloy 625 a proven material for use in the chemical and petrochemical processing systems for use in aggressive and high temperature media.

Nickel-Chromium-Iron Alloy 825: Containing 30 % iron concentration, Incoloy 825 is also counted as the member of austenitic stainless steel family. Its wide use in the sulfuric and phosphoric acid applications similar to alloy 20, are the chief development targets. However adequately resistant to HCl acid, Incoloy 825 attains chloride pitting and crevice attack specifically in sluggish and unaerated solutions. The presence of high iron concentration makes grade 825 less resistant as compare to higher nickel based alloys to alkali and halogen attack.

Nickel-Chromium-Iron-Molybdenum G Grades: Hastelloy G-3 provides enhanced attack resistance than Monel 400, Inconel 600 and Incoloy 825 in the diverse applications. It is particularly resistant to H2SO4 and contaminated H3PO4 and can perform significantly in the severe oxidizing and reducing media. The latest developed super alloy G-30 offers enhanced weldability and resistance to all types of corrosion and also in weld heat affected zones.

Nickel-Chromium-Molybdenum C Grades- Hastelloy C – 276 is the premiere material used in the chemical processing units fit for use in the extremely severe corrosive conditions where stainless steels fail easily. Alloy C276 offers excellent resistance to wide range of acids, acidic salts, and other severe conditions that occur in the chemical processing units. It is specifically useful in these intense conditions including wet chlorine and hypochlorites due to presence of molybdenum. Inconel C-276 is extremely resistant to chloride induced pitting and crevice attack.

The search for materials exhibiting better metallurgical and corrosion resistance properties than Hastelloy C-276 has led to the development and commercialization of various type grades such as Hastelloy C-22, C2000, 622, 59 and 686.

They have almost similar molybdenum concentration however much higher chromium concentration as compare to that present in Alloy C-276. Some grades also consist of tungsten and copper. The influence of these minor alloying constituents on metallurgical characteristics and corrosion resistance is composite and beyond the scope of this article.

Nickel-Molybdenum B alloys- Alloy B-2 offer outstanding resistance to sulfuric acid, phosphoric acid and hydrochloric acid in the reducing media. It is specifically suitable for systems handling hydrochloric acid at the all limits of concentration and temperature up to boiling point.

The oxidizing media adversely affect the corrosion resistance, preferably the strong oxidizers such as ferric and cupric salts that may exist as impurities. Latest produced Hastelloy B-3 offers better performance than grade B-2. The key advantages of this latest grade is reduced production of unwanted microstructures while fabrication that can cause embrittlement.

**Discovery of Nickel based alloys**

Similar to copper and iron, nickel has been being utilized in the formation of alloys since beginning of human culture. Although as compare to steels; brass, bronze and nickel based alloys are the new materials to the chemical units.

The first nickel alloy that proved of commercial significance is Monel 400, made and commercialized by Nickel Co. in 1905. Second popular materials invented are Hastelloy B and Hastelloy C. Third essential members of nickel based alloys family are Inconel 600 developed in 1931 and Incoloy in 1949. Increasing the popularity of these industrial materials, they became a proven material as heat and corrosion resistance alloys.

**Pickling of nickel alloys to prevent heat and corrosive attack**

The potential to prevent attack in heat and corrosive media makes Nickel alloys a prominent selection for severely high temperature media. The Nickel alloys are used in the extensive range of applications in the chemical processing systems at high temperatures, generally above 1000oF.

In many cases, high strength, chemical resistant nickel alloys are the suitable material when the service conditions are not tolerable by austenitic and superaustenitic stainless steels. However costlier than iron based alloys, heat and corrosion resistant nickel alloys usually are the fit and most economical prolong service materials.

Chemistry of heat and corrosion resistant nickel alloys that are extensively used in chemical processing systems is described in the following table:

| Alloy | UNS | Nickel | Chromium | Molybdenum | Iron | Tungsten | Cobalt | Others |
|---|---|---|---|---|---|---|---|---|
| Inconel 600 | N06600 | 75 % | 15 % | - | 8 % | - | - | - |
| Inconel 601 | N06601 | 60.5 % | 23 % | - | 14.4 % | - | - | 1.4 Al |
| Inconel 617 | N06617 | 52 % | 22 % | 9 % | 1.5 % | - | 12.5 % | 1.2 Al |
| Inconel 625 | N06625 | 61 % | 21.5 % | 9 % | 2.5 % | - | - | 3.8 Nb +Ta |
| Hastelloy X | N06002 | 47 % | 21.8 % | 9 % | 18.5 % | - | 1.5 % | 1.4 Al |
| Haynes 214 | N07214 | 75 % | 16 % | - | 3 % | - | 4.5 Al | - |

However the traditional alloys are no more patent protected, they are still widely known by their original trade names. For example, grades 600, 601 and 625 are generally linked with Inconel trademark. Alloy X is associated with Hastelloy trademark.

**Properties**

The physical characteristics of nickel based alloys are similar to Chromium-Nickel stainless steel 300 series. On the base of each alloy, thermal conductivity and expansion features may vary considerably and require to be counted in equipment design.

The mechanical characteristics of nickel alloys are outstanding for their strength and ductility characteristics.  Lowest room temperature strength and ductility values are stated in the following table:

| Alloy | Ultimate tensile strength, ksi | Yield strength 0.2 % offset, ksi | Elongation |
|---|---|---|---|
| Inconel 600 | 80 ksi | 35 ksi | 30 % |
| Inconel 601 | 80 ksi | 30 ksi | 30 % |
| Inconel 617 | 95 ksi | 35 ksi | 30 % |
| Inconel 625 | 100 ksi | 40 ksi | 30 % |
| Hastelloy X | 95 ksi | 35 ksi | 35 % |
| Haynes 214 | 110 ksi | 65 ksi | 25 % |
| Alloy 230 | 110 ksi | 45 ksi | 40 % |
| Alloy 242 | 184 ksi | 113 ksi | 38 % |
| Alloy 333 | 80 ksi | 35 ksi | 30 % |
| Alloy 45TM | 90 ksi | 35 ksi | 35 % |
| Alloy 602CA | 94 ksi | 43 ksi | 30 % |

Excluding alloy 601, lowest yield strengths are above 30 ksi that is a value for common austenitic stainless. The higher strength for nickel base materials compared to iron based materials increases significantly with increase in temperature as described in the following table:

Standard hot yield strength, 0.2% offset, ksi

| Alloy | Ambient | 1000oF | 1200oF | 1500of | 1800of |
|---|---|---|---|---|---|
| SS 304 | 42 ksi | 18 ksi | 16 ksi | 10 ksi | - |
| SS 309 | 45 ksi | 26 ksi | 23 ksi | 18 ksi | - |
| SS 310 | 45 ksi | 25 ksi | 21 ksi | 15 ksi | - |
| Incoloy 800H | 29 ksi | 17 ksi | 15 ksi | 13 ksi | 9 ksi |
| Inconel 600 | 50 ksi | 40 ksi | 37 ksi | 20 ksi | 9 ksi |
| Inconel 601 | 40 ksi | 32 ksi | 28 ksi | 20 ksi | 7 ksi |
| Inconel 617 | 45 ksi | 32 ksi | 34 ksi | 35 ksi | 18 ksi |
| Inconel 625 | 48 ksi | 32 ksi | 35 ksi | 38 ksi | 18 ksi |
| Hastelloy X | 49 ksi | 33 ksi | 30 ksi | 26 ksi | 18 ksi |
| Haynes 214 | 82 ksi | 72 ksi | 76 ksi | 81 ksi | 8 ksi |
| Alloy 230 | 57 ksi | 40 ksi | 39 ksi | - | 21 ksi |
| Alloy 242 | 113 ksi | 70 ksi | 76 ksi | 50 ksi | 28 ksi |
| Alloy 333 | 43 ksi | 25 ksi | 25 ksi | 24 ksi | 10 ksi |
| Alloy 45 TM | 53 ksi | 36 ksi | 34 ksi | 28 ksi | - |
| Alloy 602 CA | 50 ksi | 38 ksi | 37 ksi | 31 ksi | 13 ksi |

As shown above at 1,500oF, the nickel alloys keep 40% - 75 % of their room temperature yield strength as compared to only 20% to 35% for stainless steels.

Standard creep rupture strength

| Alloy | Condition | Stress rupture in 1,000 hours | | |
|---|---|---|---|---|
| | | 1400oF | 1600 of | 1800of |
| SS 304 | Annealed | 7.4 | 3 | 1.2 |
| SS 309 | Annealed | 7.2 | 2.7 | 1 |
| SS 310 | Annealed | 7.4 | 3 | 1.2 |
| Incoloy 800H | Solution annealed | 10 | 4.9 | 2 |
| Inconel 600 | Solution treated | 8.1 | 3.5 | 1.8 |
| Inconel 601 | Solution treated | 9.8 | 4.4 | 2.2 |
| Inconel 617 | Solution annealed | 22 | 8.4 | 3.6 |
| Inconel 625 | Solution treated | 22 | 7.5 | 2.7 |
| Hastelloy X | Solution treated | 16 | 6.5 | 2.1 |
| Haynes 214 | Solution annealed | 24 | 7.8 | 1.7 |
| Alloy 230 | Solution annealed | 19 | 9 | 2.8 |
| Alloy 242 | Annealed & aged | 15 | - | - |
| Alloy 333 | Solution treated | 14 | 5.2 | 2.1 |
| Alloy 45TM | Solution treated | 6.1 | 2.9 | 1.5 |
| Alloy 602CA | Solution treated | 8 | 4.5 | 2.4 |

While stainless steels basically lose the significant strength at temperatures about 2000oF and above, nickel alloys can still perform suitably for moderately stressed parts. For instance, the 1000 hour rupture strength at 2000of is about 1 ksi for Inconel 600, Inconel 601, Inconel 214, Inconel 230 and Inconel 333 and 1.4 ksi for Inconel 617 and alloy 602CA.

**Metallurgical stability**

Another essential characteristic in the selection of alloy for employing in the elevated temperature applications is metallurgical stability that is also called as thermal stability. It states the resistance to produce brittle microstructural phases or precipitates by aging such as after exposure to high temperatures for prolong exposure at high temperatures hence called age embrittlement manifests basically as lowered ductility and hardness and may also decrease corrosion resistance.

However alloys for example Inconel 600 and Inconel 601 are virtually resistant to age embrittlement normally undergo different extents of impairment. Among these severely affected is grade 625 that may suffer a significant reduction in ductility and impact strength when subjected at the limits from 1200of to 1400of. At the elevated temperatures, these characteristics are partly restored because the brittle precipitates redissolve. The system failures caused by decreased ductility and hardness are irregular that can be attributed to the extremely high initial characteristics standard of unaged nickel alloys.

**Chemical Resistance**

The most common form of corrosion in the elevated temperature chemical processing conditions is gaseous corrosion such as oxidation, sulfidation, chlorination and fluoridation. Other kinds of attacks occurred in the severe high temperature conditions are carburization, nitridation and hydrogen corrosion. These are not categorized as corrosion in the traditional sense, as there is no material loss or surface collapse. Instead the damage manifests as metallurgical or mechanical impairment –generally in the form of embrittlement.

The directional influence of alloying constituents on either preventing or increasing the elevated temperature chemical corrosion of the nickel based alloys is shown in the following table:

| Corrosive mode | Nickel | Iron | Chromium | Molybdenum | Cobalt | Tungsten | Antimony | Silicon | Aluminum | Titanium |
|---|---|---|---|---|---|---|---|---|---|---|
| Oxidation | Increases resistance | Lowers resistance | Increases resistance | Lowers resistance | Increases resistance | Lowers resistance | Lowers resistance | Increases resistance | Increases resistance | Lowers resistance |
| Sulfidation | Lowers resistance | Increases resistance | Increases resistance | - | Increases resistance | - | - | Increases resistance | Increases resistance | - |
| Chloridation | Increases resistance | Lowers resistance | Increases resistance | Depends on services media | Depends on services media | Depends on services media | - | Depends on services media | Increases resistance | - |
| Fluoridation | Increases resistance | Lowers resistance | Lowers resistance | Increases resistance | - | - | Lowers resistance | Lowers resistance | - | Lowers resistance |
| Carburization | Increases resistance | Increases resistance | Increases resistance | Increases resistance | - | Increases resistance | Increases resistance | Increases resistance | Increases resistance | Increases resistance |
| Nitridation | Increases resistance | Lowers resistance | Depends on services media | - | Increases resistance | - | - | Increases resistance | Depends on services media | Lowers resistance |

The influence of chromium, molybdenum, cobalt, tungsten, silicon and aluminum may be suitable or damaging on the base of specific exposure media, particularly temperature and reducing versus oxidizing conditions.

In specific, many material failure modes may occur all together. For instance, the industrial conditions comprising of both oxygen and chlorine subjecting metals to oxychlorination are extremely severe forms of corrosion. Severely corrosive attack can also be caused by liquid forms such as molten metal, salts or ash. These intense environments hardly occur in the chemical processing units.

**Types of corrosion**

The general forms of elevated temperature chemical corrosion are stated as following.

Oxidation: the most common and general kind of corrosion that occurs at the high temperatures, it is attributed by the production of metal oxide corrosive materials that are called scaled which are thick and firm so further corrosion is prevented. But in the vigorous conditions oxide layers are penetrated or removed.

Chromium is a significant element in providing the oxidation resistance to nickel alloys.

Sulfidation: It produces layers of metal sulfides that occur slightly, if any security from the further corrosion is provided. The reducing sulfur conditions are generally more aggressive than oxidizing sulfur based conditions. Nickel alloys are more prone to sulfidation as compare to stainless steel grades due to the production of easily miscible nickel sulfide. Chromium element helps in providing significant corrosion resistance.

Chloridatio : At the high temperatures, service media including chlorine and its compounds quickly attack the stainless steel grades. Because iron chlorides and oxychlorides are extremely volatile, intense chloridation may occur without significant scaling. The Nickel alloys are much more resistant as compare to iron based alloys, therefore they are the recommended material for operation in the chlorine based service conditions.

Carburization: In the intense carbon based conditions, carbon diffuses into the metal to produce the metal carbides, this kind of corrosion is named carburization that causes severe reduction in mechanical properties of a metal such as ductility and impact strength. Nickel alloys offer good resistance to carburization.

Nitridation: Usually named nitriding, it states the nitrogen diffusion into the metal lattice to produce the metal nitrides. In the chemical processing plants, it occurs specially in the high temperature ammonia based conditions. As in carburizing conditions, failure manifests not as material loss in fact as embrittelment. Nickel does not produce nitrides that refer to outstanding resistance to nitridation in nickel based alloys.

Internal corrosion: Carburization and nitridation are not the only high temperature metal loss mechanism attributed by internal depletion. Actually, the whole types of high temperature corrosive attacks are diffusion based and featured by the significant surface attack normally along grain boundaries. This is implemented to oxidation, sulfidation and particularly to halogenations. In several cases, internal corrosion gets deeper into the metal as compare the surface metal loss. Analysis of elevated temperature corrosion must hence be based not just on thickness or weight loss, even also on metallographic evaluation.

**Cost of heat & corrosion resistant alloys**

The alloys evaluated in this article are almost 2 to 5 times more expensive than grade 310 SS. The cost differences are significantly lower on the base of installed system widely because the fabrication cost doesn't vary extensively between nickel super alloys and stainless steels.

Another essential factor in cost evaluation is the higher potential, lower maintenance and longer service of the nickel alloys. Therefore considering the complete life cycle cost, nickel alloys usually prove to become the best economical selection.