Langley Alloys

# An Introduction to Nickel-Based Alloys

Nickel Alloys


## **Summary** Nickel-based alloys

- cover a wide family of different alloys, due to the ability of nickel to readily alloy with chromium, molybdenum, copper and iron
- can provide very high levels of yield strength through precipitation strengthening
- offer good to excellent levels of corrosion resistance in seawater, acids and alkalis
- can be used in applications from cryogenic to elevated temperatures
- can retain most of their strength and impact properties up to 650˚C
- are resistant to stress corrosion cracking


## Introduction

Nickel is a widely abundant element, but was difficult to extract commercially until the 20th century, which helpfully coincided with the development of stainless steels of which it is a key alloying addition. However, it was found to alloy readily with many other metals, such as chromium, molybdenum, copper and iron, to create a range of nickel-based alloys with diverse applications. These nickel-based alloys were found to have excellent corrosion resistance and be able to withstand high temperatures, making them suitable for the chemical process industry and support the development of the jet engine.

## The families of nickel-based alloys

Much of the development of nickel-based alloys was undertaken by Special Metals Corporation and companies that make up their current organisation, such as Wiggins (UK). The development of new alloys clustered around particular groups of elements, which are more widely recognised by the tradenames that Special Metal Corporation created. Such is the value of these tradenames, they are widely used despite manufacture now being undertaken by a larger number of other mills.

### i) Nickel-Copper Alloys

Nickel-copper alloys were amongst the very first developed commercially around 1906. They are designed around a nickel base with around 30% copper content, and are better known by the Special Metals Corporation tradename Monel®.

This family of alloys includes:

- Alloy 400 (Monel® 400, UNS N04400, 2.4360)
- Alloy K-500 (Monel® K-500, UNS N05500, 2.4375)

Originally developed by the International Nickel Company in the early 1900’s, Alloy 400 was the first product offered in a family of subsequent developments and was based upon the ratio of nickel and copper found in naturally occurring ores from Canadian mines. As an ore is normally a very stable composition, following this approach resulted in an alloy that was equally stable, and resistant to corrosion. As the first grade brought to market, it was widely used in applications as diverse as roofing and appliances. With many of these applications subsequently served by the development of stainless steels, its use has become much more closely associated with the chemical process industry and marine components.

However, the strength level of Alloy 400 limits it to more architectural applications. Therefore Alloy K500 was developed to overcome this limitation. It has effectively the same composition as Alloy 400, but with small additions of both aluminium and titanium (3-4% in total). The aluminium and titanium combine to form microscopic precipitates, which can be controlled through heat treatment. After forging or rolling, the round bars are subjected to an ageing heat treatment where they are held at an elevated temperature for several hours and allowed to cool slowly in air. This process ensures that as much of the aluminium and titanium is able to precipitate out of solution and form a widely-dispersed fine network. These precipitates create a significant uplift in mechanical properties – the yield strength can be up to 4x greater, and the tensile strength up to 2x greater.

### ii) Nickel-Chromium Alloys

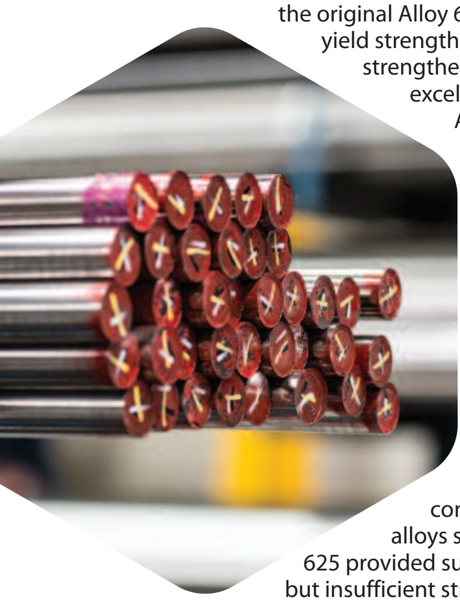
Nickel-chromium alloys are probably the most widely used nickel-based alloys. They are characterised by their excellent corrosion resistance at both ambient and elevated temperatures – forming a protective film that prevents further oxidation and retention of their mechanical properties over a wide temperature range. They are better known by the Special Metals Corporation tradename Inconel®, or the Haynes International Inc. trademark Hastelloy®.

There are at least fifteen commercially-available nickel-chromium grades, with the potential for further development and refinement to support new applications. However, the most common grades include:

- Alloy 625 (Inconel® 625, UNS N06625, 2.4856)
- Alloy 725 (Inconel® 725, UNS N07725)
- Alloy 718 (Inconel® 718, UNS N07718, 2.4668)
- Alloy C276 (Hastelloy® C276, UNS N10276, 2.4819)

Alloy 625 was developed in the 1960's and achieves reasonably high strength through the addition of molybdenum and niobium to the nickel-chromium base. This imparts solution-strengthening, meaning that no additional heat treatment stage is required. It retains much of its strength up to 800˚C and down to cryogenic temperatures. Corrosion resistance is excellent in the most aggressive of environments, as it is particularly resistant to pitting and crevice corrosion with a pitting resistance equivalent number (PREN) of over 45.

Alloy 725 is a slightly more recent development based upon the original Alloy 625, but effectively doubling its yield strength through precipitation strengthening. It therefore retains the excellent corrosion resistance of Alloy 625, but with the very high strengths of grades such as Alloy 718.



Alloy 718 was introduced in the 1960's and initially used in the aerospace industry, but due to its ready availability in the market it was taken-up by the oil and gas industry. This was associated with wells moving offshore, drilling deeper with higher temperatures, pressures and corrosive contaminants. Other nickel-based alloys such as Alloy C276 and Alloy 625 provided sufficient corrosion resistance, but insufficient strength without extensive cold working. Martensitic stainless steels were limited by their potential for hydrogen embrittlement and stress corrosion cracking. Therefore, Alloy 718 quickly became a default choice for many pressure-containing and load-bearing components in aggressive environments.

Alloy C276 is extremely corrosion resistant, due to its significant molybdenum content. It is well-suited to environments containing both sulphuric and hydrochloric acid, the latter of which is not compatible with stainless steels, although it is less well-suited to nitric acid. However, the high molybdenum and nickel content makes it an expensive alloy, so applications tend to be restricted to more niche applications, such as pharmaceutical manufacture, power generation and chemical processing.

### iii) Nickel-Iron-Chromium Alloys

Nickel-iron-chromium alloys are a leaner i.e. lower cost, alternative to nickel-chromium alloys, as a significant proportion of the expensive nickel content is replaced with iron. These grades typically contain 30-40% nickel, whereas the nickel-chromium ones are 50-60% nickel.

This family of alloys is better known by the Special Metals Corporation tradename Incoloy®, and contains over 20 different grades, including:

- Alloy 825 (Incoloy® 825, UNS N08825, 2.4858)
- Alloy 925 (Incoloy® 925, UNS N09925)

The most popular grade within the family, Alloy 825, was developed in the 1950's. It achieves excellent resistance to both oxidising and reducing acids due to its molybdenum and copper additions. Although its yield strength is quite modest, it retains its mechanical properties up to 500ºC. Therefore, it is commonly used in applications such as heat exchangers and evaporators, where the strength and corrosion resistance of super duplex stainless steels may not be required, but the operating temperature is beyond their specification.

Alloy 925 is largely based upon Alloy 825, and therefore has near identical corrosion resistance. As with Alloy 725 (based upon Alloy 625) it uses additions of titanium and aluminium to provide precipitation strengthening during further heat treatment. This ageing process increases the minimum yield strength by a factor of 4, approaching that of Alloy 718. Although it cannot compete with Alloy 718 in terms of corrosion resistance or working temperature range, it is gaining interest as a lower cost alternative.

| UNS Grade | Tradename | Ni | Cr | Mo | Cu | Fe | C | Mn | P | S | Si | Al | Ti | Nb | Other |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **UNS N04400** | Alloy 400, Monel® 400 | 63.0 | | | 28.0 - 34.0 | 0.024 | | 0.3 | 0.5 | | | 2.5 | | | N 0.2 |
| **UNS N05500** | Alloy K-500, Monel® K-500 | 63.0 | | | 27.0 - 33.0 | 2.0 | 0.3 | 1.5 | | 0.01 | 0.5 | 2.30 - 3.15 | 0.35 - 0.85 | | |
| **UNS N06625** | Alloy 625, Inconel® 625 | 58.0 | 20.0 - 23.0 | 8.0 - 10.0 | | 5.0 | 0.1 | 0.5 | 0.015 | 0.015 | 0.5 | 0.4 | 0.4 | 3.15 - 4.15 | |
| **UNS N07725** | Alloy 725, Inconel® 725 | 55.0 - 59.0 | 19.0 - 22.5 | 7.0 - 9.5 | | | | | 0.015 | 0.010 | 0.2 | 0.4 | 1.0 - 1.7 | 2.75 - 4.0 | |
| **UNS N07718** | Alloy 718, Inconel® 718 | 50.0 - 55.0 | 17.0 - 21.0 | 2.80 - 3.30 | 0.3 | | 0.1 | 0.35 | 0.015 | 0.015 | 0.35 | 0.2 - 0.8 | 0.65 - 1.15 | 4.7 - 5.5 | Co 1 |
| **UNS N08825** | Alloy 825, Incoloy® 825 | 38.0 - 46.0 | 19.5 - 23.5 | 2.5 - 3.5 | 1.5 - 3.0 | 22.0 | 0.05 | 1.0 | | 0.03 | 0.5 | 0.2 | 0.6 - 1.2 | | |
| **UNS N09925** | Alloy 925, Incoloy® 925 | 42.0 - 46.0 | 19.5 - 22.5 | 2.5 - 3.5 | 1.5 - 3.0 | 24.0 | 0.025 | 1.0 | 0.02 | 0.003 | 0.35 | 0.1 - 0.5 | 1.9 - 2.4 | 0.08 - 0.50 | |
| **UNS N10276** | Alloy C276, Hastelloy® C276 | 55.0 | 14.5 - 16.5 | 15.0 - 17.0 | | 4.0 - 7.0 | 0.01 | 1.0 | 0.04 | 0.03 | 0.08 | | | | W 3.0 - 4.5, Co 2.5, V 0.35 |

| UNS Grade | Tradename | Yield Strength (ksi) | Ultimate tensile Strength (ksi) | Elongation (%) |
|---|---|---|---|---|
| **UNS N04400** | Alloy 400, Monel® 400 | 25 | 70 | 35 |
| **UNS N05500** | Alloy K-500, Monel® K-500 | 100 | 140 | 20 |
| **UNS N06625** | Alloy 625, Inconel® 625 | 60 | 120 | 30 |
| **UNS N07725** | Alloy 725, Inconel® 725 | 120 | 165 | 20 |
| **UNS N07718** | Alloy 718, Inconel® 718 | 120 | 150 | 20 |
| **UNS N08825** | Alloy 825, Incoloy® 825 | 35 | 85 | 30 |
| **UNS N09925** | Alloy 925, Incoloy® 925 | 110 | 140 | 18 |
| **UNS N10276** | Alloy C276, Hastelloy® C276 | 55 | 100 | 60 |

*Notes on table above:*

*1) properties will vary by bar diameter. Those shown are for mid-sizes, c.100mm diameter.*

*2) several strength levels are available for certain alloys. Those shown are the most commercially-popular specifications.*

## Composition of Nickel-Based Alloys

The composition of nickel-based alloys stocked by Langley Alloys can generally fit within families, based upon their primary composition, such as nickel-copper, nickel-chromium and nickel-iron-chromium. Nickel content tends to dominate the alloy cost, followed by molybdenum. Therefore, Alloy C276 is generally the most expensive to produce, followed by Alloy 625, Alloy 718, Alloy 400 and then Alloy 825. The production costs of Alloy K-500, Alloy 725 and Alloy 925 sit above those of the alloys most similar in composition, due to their additional alloying and heat treatment costs to achieve precipitation strengthening.

## Mechanical Properties of Nickel-Based Alloys

There is significant variance in the mechanical properties available from nickel-based based, from relatively low-strength alloys like Alloy 400 supplied in the solution annealed condition, up to very high-strength alloys such as Alloy 718, supplied in the precipitation treated condition.

## i) Precipitation Treated

There are multiple terms for the precipitation treating of nickel alloys, including aged, age hardened or precipitation strengthened. The objective is to form very fine precipitates, widely dispersed throughout the bar. These act to 'pin' microstructural features (grain boundaries) and restrict them from moving when the metal is subjected to an external load. However, this complex metallurgical process can be simply described in a number of steps.

Firstly, the alloy will be formulated with elements such as titanium, aluminium and niobium, which have limited solubility within the nickel-based alloy.

Secondly, the alloy bar is solution annealed after forging or rolling. Solution annealing involves holding the bar at an elevated temperature, typically around 1000ºC for several hours. This ensures that all the individual elements within that particular item are 'dissolved' and spread throughout the bar.

Thirdly, the bar is normally quenched in water. Rapid cooling ensures there is little opportunity for the microstructure to develop as the bar slowly cools. In effective, it 'freezes' the microstructure and compositional uniformity achieved by solution annealing.

Finally, the ageing process involves re-heating the bar to an intermediate temperature, such as 500-600°C, and holding it there for many hours. The objective here is to encourage the precipitation of small particles, composed of those elements added which have limited solubility. It is a thermodynamic process, so increasing the temperature and time of the ageing process will encourage as much of these elements to be precipitated as possible. However, too high temperatures will lead to the precipitates agglomerating, joining together to form fewer but larger particles which is less advantageous for the strengthening mechanism.

The ageing process can be undertaken over a number of different steps of varying temperature and time. For some alloys this can lead to the same grade being available in multiple conditions – the obvious example being Alloy 718, offered with yield strengths of 120ksi, 140ksi and 150ksi.

Alloys 718, 725, 925 and K-500 all utilise precipitation treatment to achieve significantly increased strengths, whilst still retaining much of the toughness (impact strength) and formability (elongation) of the base alloys.

## ii) High Temperature Properties

Nickel and its alloys are well-suited to high temperature applications as most other metals are either brittle or oxidise when exposed to elevated temperatures. However, nickel-based alloys will quickly form a protective oxide layer when heated in an atmosphere containing oxygen, thereby preventing further oxidation. It also has a relatively high melting point. This means that only a handful of more exotic alloys are able to better the performance of nickel-based alloys at high temperatures.

Ferritic stainless steels can suffer embrittlement if subjected to long-term service at raised temperatures (so-called "475°C embrittlement"), even as low as 250°C when for extended periods. Duplex and super duplex stainless steels are limited to a similar operating temperature, above which both the impact strength and corrosion resistance will be impaired. The deleterious phase sigma will form at higher temperatures of 600-900°C, most typically associated with poor welding practices. Austenitic stainless steels are somewhat more tolerant of elevated temperatures, depending upon the alloy content. However, their lower strength levels typically restrict it from most load-bearing applications.

When reviewing high temperature properties, we are looking at how much of their mechanical properties at ambient temperature are retained, along with their resistance to creep and rupture.

The temperature up until which the following alloys retain their (ambient temperature) mechanical properties is shown below:

- Alloy 400 up to 320°C (608°F)
- Alloy K-500 up to 320°C (608°F)
- Alloy 825 up to 540°C (1004°F)
- Alloy 925 up to 540°C (1004°F)
- Alloy 625 up to 650°C (1202°F)
- Alloy 725 up to 650°C (1202°F)
- Alloy 718 up to 650°C (1202°F)
- Alloy C276 up to 650°C (1202°F)

Above these temperatures, the tensile strength in particular will drop quite rapidly. As the oxidation resistance of these alloys is still strong beyond 1000°C, they can be used in temperatures up to this level, but with limited load-bearing capabilities.

Creep is the slow deformation of components that can occur at higher temperatures, but where the load is appreciably less than the room temperature yield strength. Those alloys strengthened by precipitation treatment (Alloy K-500, Alloy 718, Alloy 725, Alloy 925) tend to have improved creep resistance. The precipitates that improve their strength also limit the movement of microstructural ground boundaries, and the temperatures relevant to creep have negligible impact upon the precipitates.

## Machining and Welding of nickel-Based Alloys

The properties that make nickel-based alloys interesting for many applications are also responsible for the difficulties experienced during machining. The highest strength grades will obviously require more rigid tooling and machines in order to process them. Tooling can dull quickly during machining, so checking or replacing tooling often is a requirement.

Similar to austenitic stainless steels, nickel-based alloys will work harden rapidly under the pressures of the cutting operation. This will greatly influence the ideal cutting speeds and feeds. Roughing parts to close to size can help, rather than take multiple smaller passes with the associated increase in work hardening.

In addition, nickel-based alloys retain their strength at higher temperatures, so there is little softening of the chips at the tip of the tool. In order to avoid the potential for warping if there is a heat build-up in the component, ample flow of coolant or cutting fluid is generally recommended.

More encouragingly, nickel-based alloys are relatively easily to weld, more in keeping with austenitic stainless steels. The filler metal composition will normally match that of the parent metal.

## Applications for Nickel-Based Alloys

The family of nickel-based alloys is extensive, with many developed to serve a particular industry or application. The range of alloys distributed by Langley Alloys are generally specified where 'wet' corrosion is the primary concern, rather than alloys for the very high temperature applications found in aerospace or power generation.

Nickel-based alloys are included in a number of AMS specifications, or Aerospace Material Standards, defined around the requirements of aerospace applications. However, Langley Alloys chooses to offer products that are produced in accordance with API standards (American Petroleum Institute), Norsok ("Norsk Sokkels Konkurranseposisjon", Norwegian Standards) and NACE (National Association of Corrosion Engineers), which are far more commonly required for oil and gas end users.

i) Nickel-copper alloys, such as Alloy 400 (Monel® 400) and Alloy K-500 (Monel® K-500) are most widely used in the chemical process industries and marine applications. These alloys are resistant to hydrofluoric acid, sulphuric acid and alkalis. Process industry applications include doctor blades and scrapers involving organic acids, caustic soda, dry chlorine and chlorinated plastics. Other applications include pump shafts, valve stems, drill collars and instrumentation associated with petrochemical, oil and gas equipment as they have found to be resistant to a sour-gas environments and are listed within NACE MR1075 / ISO 15156.

The combination of very low corrosion rates in high-velocity sea water and high strength make it well-suited for marine shafts. In stagnant or slow-moving sea water, fouling may occur followed by pitting but this pitting slows down after a fairly rapid initial attack. Therefore, common marine industry and shipbuilding applications include propellers, shafts and fasteners.

ii) Nickel-chromium alloys, including Alloy 625 (Inconel® 625), Alloy 725 (Inconel® 725) and Alloy 718 (Inconel® 718) offer very high levels of performance, both corrosion resistance and high strength. As such, applications will tend towards more aggressive environments as load-bearing components. The list of applications in oil and gas, plus chemical process industry, is extensive but includes wellhead and downhole components, sheathing, fasteners, gate valves, choke stems, packers, tubing hangers and other items for corrosive/sour service.

Given the very wide temperature range possible for these alloys, applications can be comfortably supported from 650ºC down to cryogenic temperatures, with minor loss of mechanical properties.

iii) Nickel-iron-chromium alloys, such as Alloy 825 (Incoloy® 825) and Alloy 925 (Incoloy® 925) are particularly resistant to both oxidising and reducing acids due to their molybdenum, chromium and copper additions.

Copper additions are known to be particularly effective in improving resistance to sulphuric acid, as demonstrated by Alloy 20 (UNS S08020 / 2.4660) and the super duplex stainless steel Ferralium® 255 (F61, 1.4507).

Therefore, the most common applications for these alloys are in applications with high acidic content, such as chemical process equipment, pollution control systems and wet scrubbers, waste heat recovery exchangers, tanks, vessels and agitators, downhole (oil and gas) equipment for corrosive/sour service, and finally nuclear reprocessing and handling equipment.

Alloy 825 is the lowest cost nickel-based alloy offered, due to the lower nickel content with higher iron levels, and offers more modest strength levels only. It will tend to be used when super duplex stainless steels are not viable, either at lower temperatures (below -50ºC), slightly raised temperatures (above 250ºC) or in specific chemical solutions. However, Alloy 925 has around four times the yield strength, and can be considered as an alternative to Alloy 718 in selective applications, mostly in oil and gas-related applications such as downhole equipment.

*Ferralium® is a registered trademark of Langley Alloys Ltd.*
*Monel®, Inconel® and Incoloy® are registered trademarks of Special Metals Corporation.*
*Hastelloy® is a registered trademark of Haynes International Inc.*




**UK**
The Wharf
504-506 Lowfield Dr
Newcastle, Staffordshire
ST5 0UU
Tel: +44 (0)1782 610250
Fax: +44 (0)1782 612219
sales@langleyalloys.com

**Singapore**
9B Jalan Ampas
Singapore
329517
Tel: +65 6254 1139
SEAsia@langleyalloys.com

**US - Portland**
Langley Alloys
12323 NE 99th Street
Vancouver WA 98682
Tel: 800-878-3675
Tel: (360)-883-0569
Fax: 360-883-0764
usa@langleyalloys.com

**US - Houston**
300 Hilbig Rd
Conroe, Texas 77301-1458
United States
Tel: 281 819 5588
usa@langleyalloys.com