



## Nickel-Based Super Alloys

### Introduction

This Insight report, the twentieth in the series of INSG Insight briefing reports, provides members with information on one of the many downstream uses of nickel; the use of nickel-based super alloys. This report is intended to contribute to a better understanding by member countries on the dynamics driving the nickel market. The use of nickel in nickel-based super alloys other than stainless steel is one of the principal markets for nickel.

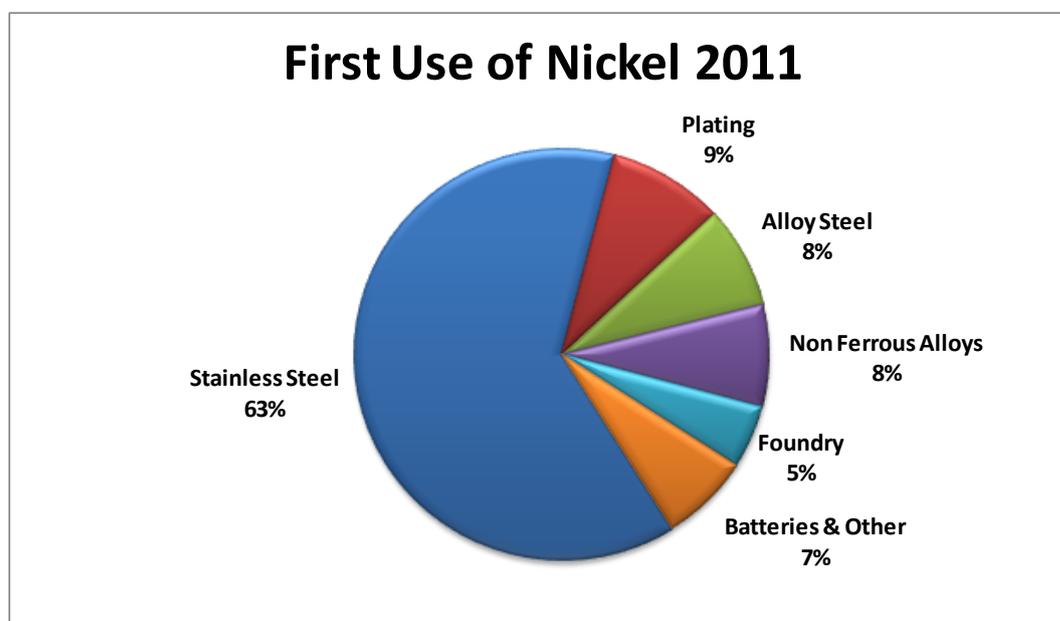
According to the Nickel Institute, the term “super alloy” is applied to alloys which have outstanding high temperature strength and oxidation resistance. Nickel-based superalloys may contain alloying additions of chromium, cobalt, aluminium, titanium, rhenium, ruthenium and other elements. Often components are produced by carefully controlled solidification in order to get an optimum directionally solidified or single crystal structure. Components fabricated from super alloys can have strengths at 1000°C which exceed that of ordinary steels at room temperature. They are essential in the hottest parts of gas turbines both for power generation and aircraft engines.

### Summary

Nickel-based super alloys are found in a wide range of applications. The most prominent use is in the manufacture of gas turbines for use in commercial and military aircraft, power generation, and marine propulsion. Superalloys also find important applications in the oil and gas industry, space vehicles, submarines, nuclear reactors, military electric motors, chemical processing vessels, and heat exchanger tubing. Several generations of super alloys have been developed, each generation tending to have higher temperature resistance. The latest generations of super alloys incorporate expensive alloying metals such as rhenium and ruthenium to achieve the desired characteristics. Because of this, the cost of some new super alloys can be five times more expensive than high-quality turbine steel. The outlook is for considerable growth in usage in these areas, in particular as the aircraft manufacturing and electrical power generation industries grow. However, the high cost of some of the alloying metals used along with nickel in super alloys may be a constraint to usage. For example, rhenium currently (March 2013) trades at about \$4200 per kilogram and ruthenium at \$65 to 85 per ounce.

## Background

While stainless steel accounts for by far the largest use of nickel, the use of nickel in nickel-based super alloys is a significant and potentially growing market for nickel. In the recent INSG publication *The Market for Nickel 2012*, the breakdown below was provided showing the relative volumes of first use of nickel in differing applications. The usage of nickel in super alloys falls under the category of Non-Ferrous Alloys in the chart below.



Source: INSG

In the chart the definition of non-ferrous materials includes products of pure nickel (98-100% nickel content), nickel base alloys (50-97% nickel), iron-nickel-chrome alloys (30-40% nickel), copper base alloys (1-49% nickel) and cladding materials. This category follows plating as one of the most important end use sectors for nickel and accounts for an estimated 8 per cent of total nickel use.

The category of non-ferrous nickel materials can be further subdivided. The transportation sector is the largest user of nickel-containing non-ferrous alloys and within this sector the aircraft and aerospace sector accounts for more than half of nickel non-ferrous alloys used. The next most significant sector is marine applications, which accounts for about a third of nickel non-ferrous alloys used in transport.

Because nickel super alloy parts and components can withstand harsh environments, and exhibit high heat resistance, corrosion resistance and acid resistance, they are ideal materials for use for pumps, valves, piping systems, process equipment, turbines and assemblies in the marine, chemical processing, oil and gas, aerospace and military industries.

Another way of looking at nickel usage is the distribution of various nickel products into the end use. The table below provides a more detailed breakdown of which nickel products are used in the various sectors, and the types of material utilized in each application. The data was gathered by Intierra and the percentage of use is slightly different from the INSG figures cited above, however the relative standing of the sectors of usage for the two sets of

data corresponds very well. As can be seen, nickel alloys account for just under 10 per cent of total nickel usage. For 2012, this level of use would correspond to approximately 162,000 tonnes of refined nickel. Nickel destined for use in alloys is sourced from three types of product: premium electrolytic nickel; pellets, powders and salts; and other electrolytic nickel.

## Nickel Usage and Sources

(In Percentage)

Category	Pellets, Powders, Salts, Ni Oxide	Premium Electrolytic Ni	Other Electrolytic	Briquettes	Ferro Nickel	Nickel Pig Iron	All Ni
Stainless Steel	7.9	0.1	13.0	9.7	18.2	16.2	65.1
Other Steel Mill	0.3	0.1	3.4	0.3	0.4		4.5
Foundry		0.1	3.4	0.4			3.9
Nickel Alloy	2.8	4.5	2.5				9.8
Electroplating	2.5	4.1	3.3				9.9
Other	2.1	2.0	2.7				6.8
<b>Total</b>	<b>15.6</b>	<b>10.9</b>	<b>28.3</b>	<b>10.4</b>	<b>18.6</b>	<b>16.2</b>	<b>100%</b>

Source: Intierra (based on 2011)

## Types of Nickel Super Alloys

Since their introduction a wide variety of nickel-containing super alloys have been developed, reflecting the evolving range of demands for this material. The Nimonic family of alloys was first developed in the 1940s by research teams in England for use in early jet engines. Nimonic alloys are a family of super alloys which typically consist of more than 50% nickel and 20% chromium with additives such as titanium and aluminium. Another family of super alloys is the Inconel alloys, which are made using nickel, chrome and some iron. These nickel-chromium and nickel-chromium-iron series of alloys led the way to higher strength and resistance to elevated temperatures. Today they are used for both commercial and military engine systems. Two of the earliest developed Ni-Cr and Ni-Cr-Fe alloys were Inconel Alloy 600 and Nimonic Alloy 75.

Super alloys can be polycrystalline, have a columnar grain structure, or be a single crystal. Single-crystal super alloys (SX or SC super alloys) are formed as a single crystal using special solidification techniques. The opposite of a single crystal is an amorphous structure where the atomic position is limited to short range order only. In between the two extremes is polycrystalline, which is made up of a number of smaller crystals.

Turbine blades have been made from nickel-base single crystal super alloy for many years. The first generation of single crystal superalloys contained no rhenium. Second generation single crystal super alloys were developed in the late 1980s and are often used in both commercial and military aircraft engines. These alloys typically contain 3 percent rhenium by weight, which distinguishes them from first generation single crystal superalloys. Examples of second generation alloys include Rene N5, CMSX-4, and PWA 1484. Third generation alloys were designed to increase the temperature capability and creep resistance further. These alloys have rhenium levels above 5.5 percent and may contain hafnium. Examples of these alloys include Rene N6 and CMSX-10. A fourth generation alloy (EPM 102) was developed in the 1990s with NASA

sponsorship; it is a very strong alloy due to the increased levels of rhenium and other refractory metals. The fourth generation alloy EPM 102 is about 6% heavier than second generation alloys. This weight increase may seem small, but any weight increase to the turbine blade also cascades to the disk and shaft and increases the overall system weight by a factor of 8 to 10x. Later generation alloys tend to have high alloy densities and this can limit the use of the super alloy, and third and fourth generation alloys are used only in specialized applications.

In 2008, two fifth generation nickel-based single crystal superalloys, TMS-162 and TMS-173, were developed in Japan. Both alloys exhibit excellent creep resistance. The composition of these alloys includes molybdenum and rhenium in conjunction with a high ruthenium (a platinum group metal) concentration to achieve the desired structure.

A listing of some of the super alloys, with information on their composition and some of the uses is provided here.

- Inconel Alloy 600 (76Ni-15Cr-8Fe) is a standard material of construction for nuclear reactors, also used in the chemical industry in heaters, stills, evaporator tubes and condensers,
- Nimonic alloy 75 (80/20 nickel-chromium alloy with additions of titanium and carbon) used in gas turbine engineering, furnace components and heat-treatment equipment
- Alloy 601. Lower nickel (61%) content with aluminium and silicon additions for improved oxidation and nitriding resistance chemical processing, pollution control, aerospace, and power generation
- Alloy X750. Aluminium and titanium additions for age hardening. Used in gas turbines, rocket engines, nuclear reactors, pressure vessels, tooling, and aircraft structures.
- Alloy 718. (55Ni-21Cr-5Nb-3Mo). Niobium addition to overcome cracking problems during welding. Used in aircraft and land-based gas turbine engines and cryogenic tankage
- Alloy X (48Ni-22Cr-18Fe-9Mo + W). High-temperature flat-rolled product for aerospace applications
- Waspaloy (60Ni-19Cr-4Mo-3Ti-1.3Al). Proprietary alloy for jet engine applications
- ATI 718Plus. A lower cost alloy which exceeds the operating temperature capability of standard 718 alloy by 100 F<sup>o</sup> (55 C<sup>o</sup>) allowing engine manufacturers to improve fuel efficiency.
- Nimonic 90. (Ni 54% min Cr 18-21% Co 15-21% Ti 2-3% Al 1-2%) used for turbine blades, discs, forgings, ring sections and hot-working tools
- Rene' N6. (4Cr-12Co-1Mo-W6 -Ta7- Al5.8 - Hf 0.2 -Re5- BaNi) 3<sup>rd</sup> generation single crystal alloy used in jet engines
- TMS 162 (3Cr- 6Co-4Mo-6W-6Ta-6Al-5Re-6Ru-balance Ni) 5<sup>th</sup> generation single crystal alloy for turbine blades

(Nimonic and Inconel are registered trademarks Special Metals Corp.)

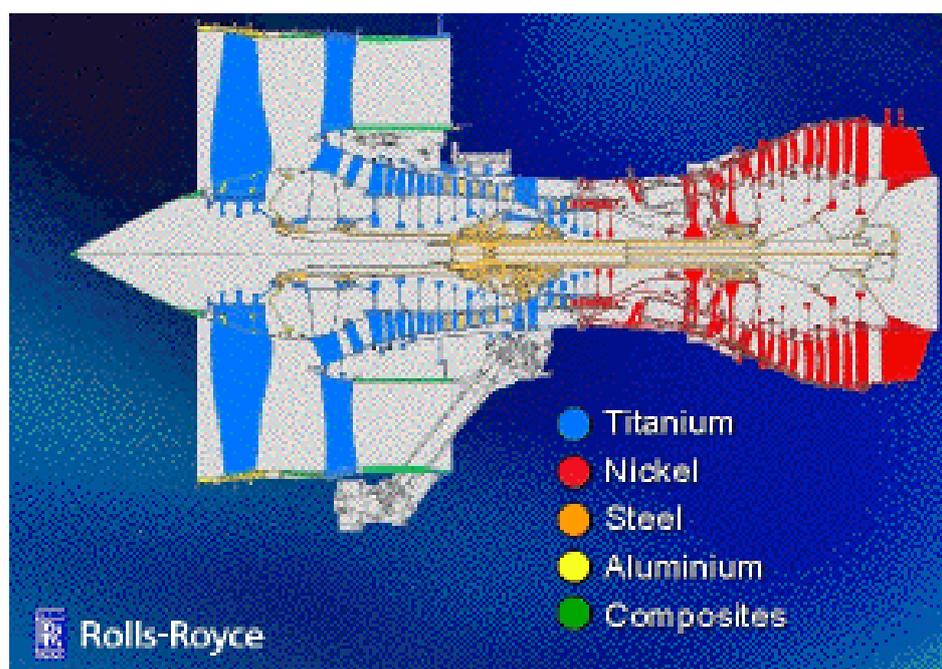
## Characteristics of Super Alloys

Nickel-containing super alloys are selected for use in certain applications due to their characteristics. Among the important characteristics are creep resistance at high temperatures, good surface stability, and corrosion and oxidation resistance. One of their most important properties is high temperature creep resistance. Creep is the tendency of a solid material to move slowly or deform permanently under stress. Creep takes place over time and results from long-term exposure to stress levels, and is more severe in materials subjected to heat for long periods at levels close to the materials melting point. For example, a turbine blade made of a non-creep resistant material and used in a high temperature environment may creep over time, contact the housing and damage the blade. Creep resistant materials play a critical role in many applications including jet engines, heat exchangers, nuclear power plants, and kilns. Component failure is often the result of creep. Another important property of super alloys is corrosion resistance. Corrosion resistance arises from the formation of a protective oxide layer which protects the underlying material.

## Applications of Super Alloys

Superalloys are commonly used in gas turbine engines in those areas of the engine that are subject to high temperatures and which require high strength, excellent creep resistance, as well as corrosion and oxidation resistance. In turbine engines this is in the high pressure turbine where blades can face temperatures approaching if not beyond their melting temperature. New jet engines are more efficient because of higher operating temperatures, requiring higher-performing components. The use of super alloys can allow the operating temperature to be increased from 1200F to 1300F. Besides increasing efficiency and power output, higher temperatures result in reduced emissions because the combustion cycle is more complete. The diagram below shows the areas within a jet engine where nickel-based super alloys are used i.e. the hottest, highest pressure zones.

### Material Use in Jet Engines



## **Outlook for Sales of Jet Engines**

Rolls-Royce Civil Aerospace is one of the largest manufacturers of jet engines. In its global market outlook, which covers passenger and cargo jets, corporate and regional aircraft, Rolls-Royce predicts that over the 20 year period 2012-2031 the global market will require 149,000 engines to be delivered, worth around US\$975 billion. These engines will be required to power 68,000 commercial aircraft and business jets. The forecast predicts global passenger traffic, as measured in Revenue Passenger Kilometres (RPKs), will increase by a compound 4.5% per annum over the period. Military sales would add to this total.

Nickel-based superalloys typically constitute 40–50% of the total weight of an aircraft engine. The alloys are used mainly in the combustor and turbine sections of the engine as these are the areas where the highest temperatures are maintained during operation.

Efforts to reduce carbon emissions and improve fuel efficiency in jet engines can be expected to continue. This will drive the demand for nickel-based super alloys in this application and may lead to the development of new generations of super alloys.

The manufacture of jet engines for commercial and military aircraft is carried out by a relatively small number of companies, among the best known are Pratt & Whitney, General Electric, Rolls-Royce and Snecma.

## **Outlook for Sales of Steam Turbines for Power Generation**

The future demand for nickel-based super alloys is correlated to the growth of generation of electricity from coal, natural gas and nuclear energy. Nickel super alloys are essential for improving energy efficiency in steam turbines used to generate electricity.

The International Energy Agency (IEA) publishes the World Energy Outlook (WEO) on a regular basis. A recent WEO projection of global energy consumption to 2030 indicates that the use of natural gas and nuclear power will grow significantly. Both of these sectors use nickel-based super alloys.

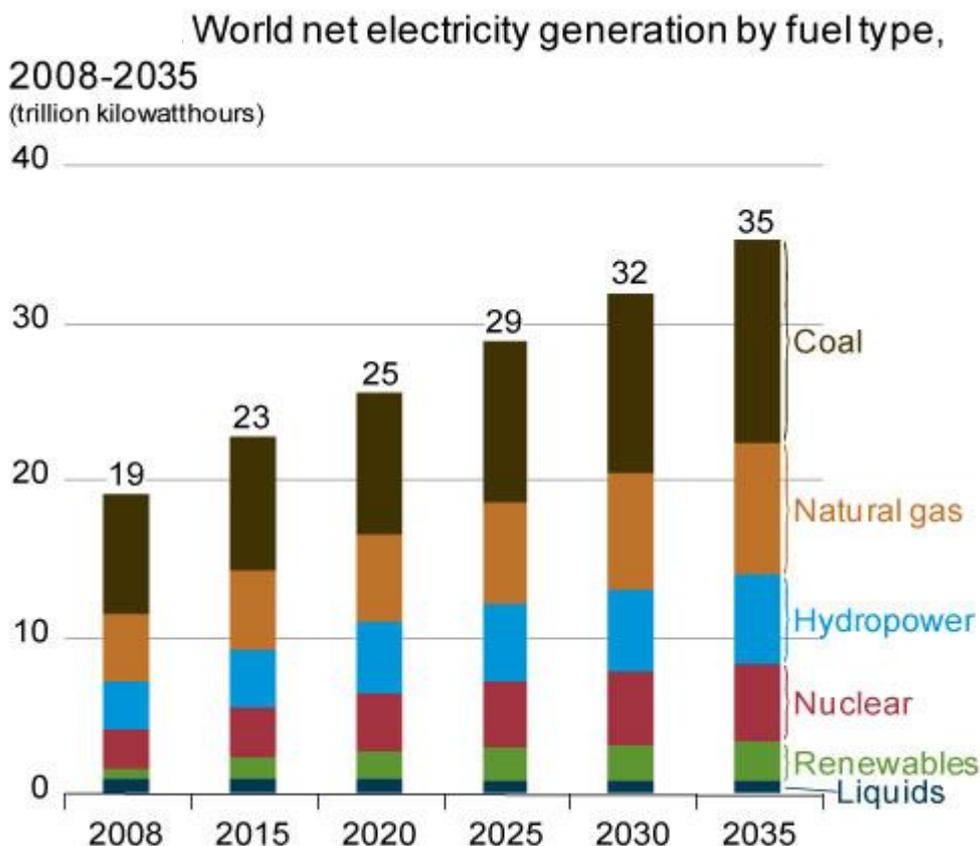
According to the IEA, the fastest growing fuels are expected to be renewables (including biofuels) with growth averaging 7.6% per annum 2011-2030. Nuclear (2.6% p.a.) and hydro (2.0% p.a.) both grow faster than total energy. Among fossil fuels, gas is projected to grow the fastest (2.0% p.a.), followed by coal (1.2% p.a.), and oil (0.8% p.a.). Overall, global electricity demand will grow by 2.2% per year, and nearly 80% of this additional demand is projected to come from non-OECD countries. Overall, the WEO projects worldwide electricity prices to increase by 15% on average in real terms over the period 2012-2035.

The United States Energy Information Agency (EIA) also makes forecasts for energy which can assist in assessing the trends in demand for nickel super alloys. In a 2011 report the EIA projects that the world's total natural gas consumption will increase by 1.6 per cent per year on average, from 111 trillion cubic feet in 2008 to 169 trillion cubic feet in 2035. Increasing supplies of

unconventional natural gas, particularly in North America but elsewhere as well, help keep global markets well supplied. As a result, natural gas prices are expected to remain more competitive than oil prices, supporting the growth in projected worldwide gas consumption. In the projection period, the most rapid expansion of natural gas use is for electric power generation and industrial use. Worldwide natural gas used for power generation is expected to increase by 2.0 per cent per year from 2008 to 2035.

The IEA projections for new nuclear plants are that an estimated additional 312 gigawatts (GW) of capacity will be installed over the next two decades, with nearly one-third to be added in China, which will entail an average of 13 GW of nuclear new facilities to be commissioned each year. The IEA forecasts that the investment for nuclear power plants is expected to be \$942 billion over the 2012-2035 period, an annual investment of \$41 billion.

Coal will continue to be a major fuel for electric power generation, even though natural gas is expected to account for a growing proportion of electricity generation. The chart below shows the EIA forecasts for electricity generation by fuel.



Source: US Energy Information Agency -International Energy Outlook 2011

Nickel super alloys can play an important role in improving energy efficiency in steam turbines used to generate electricity. On average, the world's coal-fired power plants consume 480 grams of coal, and release between 1,000 and 1,200 grams of CO<sub>2</sub>, to produce a kilowatt-hour of electricity. In all, coal-fired generation accounts for some eight billion tons of CO<sub>2</sub> emissions annually. However, the newest plants, using the most efficient systems which incorporate

super alloys, can burn as little as 320 g of coal per kilowatt-hour and emit only 761 g of CO<sub>2</sub>. New turbines under development by Siemens aim for a consumption of only 288 g of coal per kilowatt-hour, producing only 669 g of CO<sub>2</sub>. Such an improvement in fuel efficiency, if applied to all coal burning power plants, would result in considerable reductions in global CO<sub>2</sub> emissions each year.

To achieve higher efficiency in turbine generators, the steam entering the turbine should be as hot as possible and the steam leaving it as cool as possible. The blades then have the maximum available energy to convert into rotational energy, which is fed into the generator. As a result, the steam temperature needs to be increased from the level of about 600 °C typically found in the best power plants to 700 °C. This increase in temperature requires the use of materials such as nickel-based super alloys.

### **Nickel Alloys in the Oil and Gas industry**

Nickel-based super alloys are increasingly finding applications in the oil and gas sector. The environments encountered in oil and natural gas production are frequently corrosive and challenging. Often significant levels of hydrogen sulfide, carbon dioxide, chlorides, and free sulfur are present. In some of these environments high pressure and temperatures up to 450°F (232°C) can be encountered. Processing of oil and natural gas under these environmental conditions requires special materials. Nickel-base alloys 718, 725, and 925 are commonly used in oil and natural gas production. These alloys contain chrome and molybdenum which aid in resisting corrosion. Alloy 718 was initially developed for use in aerospace and gas turbines, but has become the preferred material for the manufacture of wellhead components, auxiliary and down-hole tools, and sub-surface safety valves.

### **Conclusions**

Nickel-based super alloys have an exceptional combination of high temperature strength, toughness, and resistance to degradation in corrosive or oxidizing environments. Because of these characteristics they are widely used in aircraft and power-generation turbines, rocket engines, nuclear power and chemical processing plants and other challenging environments. The availability of superalloys during past decades has led to a steady increase in the turbine entry temperatures, and this trend is expected to continue. New generations of super alloys can tolerate average temperatures of 1050°C with occasional excursions to temperatures as high as 1200°C, which is approximately 90% of the melting point of the material. Increased operating temperatures and higher efficiency in gas turbines and jet engines can reduce CO<sub>2</sub> emission, thus contributing to the slowing of climate change.

The outlook for demand for super alloys is positive. The demand for jet engines and for steam turbines for electricity generation, both large markets for super alloys, is expected to grow over the next two to three decades. However, one constraint on the growth of the super alloy market is the high cost of some of the metals, such as rhenium and ruthenium, used in creating the alloys. Future research may look at ways to reduce the cost of super alloys.

New methods for making superalloys are another focus of research. One approach, known as radiolysis, focuses on creating alloys and superalloys through nanoparticle synthesis. This process holds promise as a universal method of nanoparticle formation. Future developments may focus on reduction of weight, improving oxidation and corrosion resistance while maintaining the strength of the alloys.

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