

Introduction

Ni-base alloys are one of the most important classes of engineering materials, since they can be used in a wide range of environments and applications. These alloys are selected for both aqueous and high temperature corrosion resistance, high strength at both ambient and high temperatures, ductility and toughness at low temperatures, specific electrical properties, and many other physical property-dependent applications. The Ni-base alloy welding consumables offer some properties in the as-welded condition that no other family of welding products can offer, such as the ability to be diluted by a number of diverse alloying elements while maintaining strength and ductility from cryogenic temperatures to temperatures approaching the solidus. They are also quite versatile. For example, the family of Ni-Cr-Mo welding products is used to weld 9% Ni steel to produce excellent as-welded strength and impact toughness at liquid nitrogen temperatures. Nickel and nickel-iron alloys are used to weld cast irons because they can be diluted by iron and carbon while remaining ductile and providing good machining characteristics. They are also widely used in the power generation industry for dissimilar welds between carbon steels and austenitic stainless steels in order to provide a transition in coefficient of thermal expansion for elevated temperature service.

Relative to steels, Ni-base alloys can be used both at cryogenic temperatures and temperatures approaching 1200°C (2190°F) because the matrix of the solid solution alloys remains austenitic¹ from solidification to absolute zero. With appropriate alloying additions, these alloys provide useful corrosion resistance and have applications in a wide range of industries, including Power Generation, Petrochemical, Chemical Processing, Aerospace, and Pollution Control. Welding is a critical fabrication technique for Ni-base alloys. Considerable research and development has been conducted over the last 50 years in an effort to better understand and control the weldability of these alloys, and to develop welding consumables that meet the ever

¹Note that here and elsewhere in the text, the terms “austenite” and “austenitic” are used to refer to the face-centered cubic structure that is the predominant phase in Ni-base alloys.

increasing demands on corrosion resistance and mechanical properties of welded joints.

This book is designed to provide basic information regarding the welding metallurgy and weldability of Ni-base alloys. The text includes comprehensive coverage of the two most important classes of Ni-base alloys, namely solid-solution strengthened alloys and precipitation-strengthened alloys. One chapter is dedicated to oxide dispersion strengthened (ODS) alloys and nickel-aluminide alloys. In addition to providing basic information regarding the welding metallurgy of these alloy systems, concepts regarding weld repair, and selection and application of Ni-base alloys in dissimilar welds are addressed. Many important concepts are demonstrated through the use of “case studies” that relate these concepts to actual applications.

1.1 Ni-BASE ALLOY CLASSIFICATION

There is no systematic classification system for Ni-base alloys as there is for steels and aluminum alloys. For this reason, most Ni-base alloys are known by their trade names or by the alloy number that was originally assigned by the alloy producer. For example, INCONEL[®] alloy 600ⁱⁱ and HASTELLOY[®] alloy C-22ⁱⁱⁱ are also referred to as Alloy 600 and Alloy C-22. Ni-base alloys are generally classified by composition, as shown in Figure 1.1. The following provides a brief summary of these classifications.

1.1.1 Commercially Pure Nickel Alloys

Commercially pure nickel alloys are those that contain primarily nickel (>99wt%). There is an entire family of commercially pure nickel alloys anchored by Alloys 200 and 201. These materials have low strength and hardness, and are used principally for their corrosion resistance in caustic environments. Alloy 201 has a limit of 0.02 wt% carbon so that it can be used above 315 °C (600 °F) without the danger of being “graphitized.” Because carbon is relatively mobile in the nickel matrix above 315 °C, carbon additions beyond the solubility limit (~0.02 wt%) will result in precipitation of graphite particles that render the material brittle and weak.

There are a number of additional commercially pure nickel alloys that exist for electrical or magnetostrictive limited applications. These alloys have good weldability but are susceptible to porosity when welded. If these alloys are kept clean before and during welding, they will exhibit good resistance to cracking, but gas shielding or fluxing must be sufficient to prevent the formation of porosity. The commercially pure nickel welding consumables have additions of up to 1.5% aluminum and 2.0-to-3.5% titanium to counter the

ⁱⁱ INCONEL is a registered trademark of Special Metals, a PCC Company.

ⁱⁱⁱ HASTELLOY is a registered trademark of Haynes International, Inc.

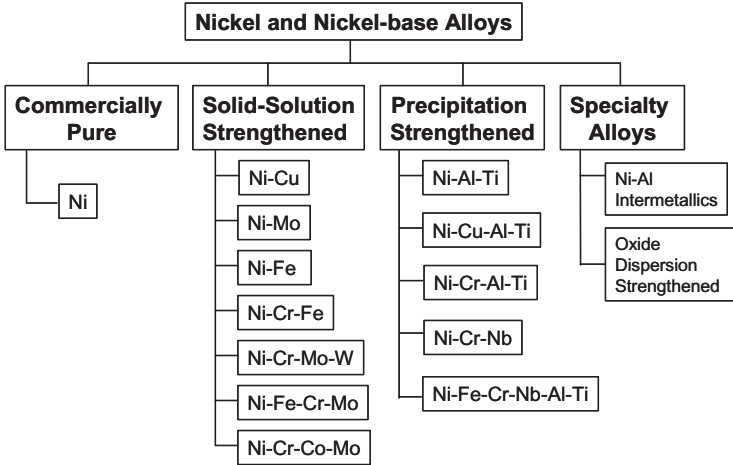


Figure 1.1 Classification of Nickel and Nickel-Base Alloys.

effects of even small amounts of atmospheric contamination. Both Ti and Al combine with oxygen to form oxides and nitrogen to form nitrides, thereby controlling porosity in the weld deposits.

1.1.2 Solid-Solution Strengthened Alloys

Nickel and copper are isomorphous (complete solid solubility), which allows production of single phase alloys over the entire composition range. This family of materials generally exhibits good corrosion resistance to seawater and other general corrosion environments. The Ni-Cu alloys are usually quite weldable, but may be susceptible to porosity if proper shielding or well-deoxidized consumables are not used. Other solid-solution strengthened Ni-base alloys may contain only iron and most of these alloys are used for their particular coefficient of expansion or electrical properties. The Ni -36 wt% Fe alloy commonly known as INVAR^{iv} exhibits the lowest coefficient of expansion of any of the Ni-base alloys and expands and contracts at a rate of less than 1.0×10^{-6} in/in/F. when heated and cooled over a range of several hundred degrees up to about 300°F. The Ni-Fe alloys have reasonable weldability, but the development of consumables with good solidification cracking resistance with near-matching expansion properties has presented a challenge to consumable manufacturers. The Ni-Fe alloys and their consumables may also be susceptible to ductility-dip cracking. This cracking mechanism is described in detail in Chapter 3.

Other solid-solution alloys contain a variety of substitutional elements including chromium, molybdenum, and tungsten. Each element imparts

^{iv}INVAR is a registered trademark of Imphy SA, France.

particular characteristics and has the ability to alter the welding response of each alloy. Maximum ultimate tensile strength values of the solid-solution strengthened Ni-base alloys approach 120 ksi (830 MPa) with yield strengths in the range of 50 to 70 ksi (345 to 480 MPa). These alloys are used in a broad range of applications requiring good corrosion resistance. If higher strength levels are required, it is necessary to select precipitation-strengthened alloys.

1.1.3 Precipitation-Strengthened Alloys

The precipitation-strengthened Ni-base alloys contain additions of titanium, aluminum and/or niobium that form a strengthening precipitate with nickel after an appropriate heat treatment. Under most conditions, these precipitates are coherent with the austenite matrix, and thus strain the matrix such that the strength of the alloy increases substantially. The most common of these precipitates are called gamma prime [γ' -Ni₃Al, Ni₃Ti, and Ni₃(Ti,Al)] and gamma double prime (γ'' -Ni₃Nb). By optimizing alloying additions and heat treatment, these alloys can be strengthened to reach ultimate tensile strength values exceeding 200 ksi (1380 MPa) with 0.2% offset yield strengths over 150 ksi (1035 MPa).

The first precipitation-hardened Ni-Cr alloy (X-750) is strengthened by gamma prime and exhibits the combination of good oxidation resistance and high temperature strength to near the gamma prime solvus temperature. Unfortunately, it is subject to postweld strain age cracking (SAC) when welded and direct-aged without an intervening annealing treatment. This cracking mechanism is described in detail in Chapter 4. In an effort to improve weldability and avoid SAC, a second generation of precipitation-hardening Ni-Cr alloys was developed that are strengthened by gamma double prime. The most popular of these alloys is Alloy 718. Because the gamma double prime precipitate forms more slowly than gamma prime, Alloy 718 is generally immune to SAC during postweld heat treatment. One of the major applications for Alloy 718 is for aerospace gas turbine shafting and pressure containment. When melted properly to produce low levels of impurities, this alloy provides tremendous design opportunities with excellent fatigue life at service temperatures up to 760°C (1400°F) when properly designed.

The precipitation-strengthened alloys are often referred to as “superalloys” based on their retention of unusually high strength and corrosion resistance at elevated temperatures. The term has been loosely applied to many other high strength complex alloys, but generally the term “superalloys” is used to describe Ni-base alloys with their superior strength properties provided by the gamma prime and gamma double prime phases.

The use of “superalloys” for rotating gas turbine blades or “buckets” began with alloys such as IN713C. This alloy was similar to Alloy X-750, but was only produced as a casting and contained such high additions of aluminum and titanium that it age-hardened upon cooling from casting temperatures. Structural repairs were limited due to its extreme susceptibility to SAC, but

blade tip build-up was performed without cracking. After decades of technological development, other members of the “superalloy” family were added to include the very high strength, corrosion-resistant single crystal turbine blade alloys. Welded blade tip buildup due to erosion during service is possible if the welding process is well controlled and the residual stresses are kept low. The primary challenges to weld repair of these materials include the avoidance of stray grains in the melt pool and elimination of cracking. Important processing considerations for repair of single crystal alloys are described in Chapter 6.

1.1.4 Other Specialty Alloys

There are other alloys that could fit into the “super” category by nature of impressive high temperature creep strength, such as the oxide dispersion strengthened alloys MA6000 and MA754^v. These alloys exhibit superior creep strength by employing both precipitation hardening and dispersion hardening created by a fine dispersion of particles that are stable at high temperatures. Ytria (Y_2O_3) is one example of the dispersoid used for strengthening. These materials also have excellent high temperature oxidation resistance, but they suffer from the inability to maintain their high strength across the weld joint when joined by conventional fusion welding techniques. When melted by fusion welding, the dispersoid tends to agglomerate and the local stiffening caused by the dispersoid is lost within the fusion zone and the heat-affected zone. Welding of ODS alloys is discussed in more detail in Chapter 5.

Nickel-aluminides are alloys designed around either the NiAl or Ni₃Al compound. They exhibit very high strength and corrosion resistance, but are very difficult to weld because of their low ductility over a wide temperature range. Ni-Cr-B and Ni-Mo-Si alloys have been developed for wear resistance in a variety of environments, but these alloys are also difficult to weld due to high hardness, low ductility and the formation of low-melting range phases within their compositions.

1.2 HISTORY OF NICKEL AND NI-BASE ALLOYS

Commercially useful Ni-base alloys were first introduced in the late nineteenth century and were developed to a high level of sophistication during the twentieth century. The element nickel was initially named by the Swedish scientist and government-sponsored mineralogist, Axel Frederik Cronstedt, in 1754 when he published “Continuation of Results and Experiments on the Los Cobalt Ore.”(1). Earlier, it was known to exist as a reddish mineral, nickel arsenate-octahydrate ($Ni_3As_2O_8 \cdot 8H_2O$) ore that became known as Annabergite after the town of Annaberg in Saxony where it was mined. It contained 29.5% Ni and is also known as nickel bloom or nickel ochre. Miners in the area of

^vThe mechanically alloyed (MA) alloys were developed by the International Nickel Company.

Erzgebirge retrieved a related red-colored ore called “nicolite” or nickel arsenide (NiAs). Because of its reddish color, the ore was initially thought to contain copper (kupfer), but when smelted, the arsenic-bearing fumes generated were extremely noxious to the smelters and the primary metal was difficult to isolate. Thus, they thought that “Old Nick,” (an early reference to satan or the devil) was involved in making their work difficult and dangerous.(2) Therefore the term “kupfer nicell” came to be applied to the ore, which literally meant “devil’s copper.” The term Kupfer-nicell was first used in 1654 near what is present day Dresden, Germany.

It wasn’t until about 100 years later that Cronstedt officially named the element nickel after much scientific inquiry. In his words, “*Kupfernickel is the ore which contains the largest amount of the semi-metal previously described, and of which an account has been published. For this reason, I have given its regulus the same name, or, for the sake of convenience, I have called it NICKEL, until it can be proved to be only a composition of metals or semi-metals previously known.*”(3) Obviously, Cronstedt had only rudimentary tools for defining or analyzing the new discovery, but his pronouncement was apocryphal and the name was adopted! Over one hundred years later, a significant ore body was discovered in the Sudbury basin in Ontario, Canada and primitive mining began in the late nineteenth century. This deposit, made up principally of sulfide compounds, also contained significant amounts of copper and became an item of great interest to the Orford Copper Company in New Jersey. About the same time, nickel was being smelted and refined in Clyddich, Wales.

The International Nickel Company (INCO) was formed from the Orford Copper Company and the Canadian Copper Company on March 29, 1902.(4) In the same year, Ambrose Monell (photo in Figure 1.2) filed a patent for one of the first nickel alloys to become commercially significant. It contained approximately 2/3 nickel and 1/3 copper and is the precursor of MONEL^{®vi} alloy 400 (70Ni-30Cu) that is still in use today. It is not accidental that this is the ratio of nickel-to-copper found in most of the ores in the Sudbury basin. This useful alloy was produced by simply refining the ore and producing the alloy from the metallic elements found naturally.

A decade later in December 1912, another nickel producer, the Haynes Stellite company, was founded by Elwood Haynes (photo in Figure 1.3) in Kokomo, Indiana.(5) Haynes had been working on nickel and cobalt alloys with additions of chromium and was eventually granted patents on Ni-Cr and Co-Cr alloys. The Ni-Cr patent was initially rejected because of competing patents by A.L. Marsh of INCO. Haynes Stellite, after 50 years of ownership by Union Carbide Corporation and another 30 years by Cabot Corporation, is now known as Haynes International with their headquarters still located in Kokomo, Indiana. Their history is well-marked by numerous popular

^{vi}MONEL is a registered trademark of Special Metals, a PCC Company.



Figure 1.2 Photo of Ambrose Monell. (From INCO archives with caption—“U.S. Patent 811,239 issued to Ambrose Monell on January 30, 1906 for a new and useful improvement in the manufacture of nickel-copper alloys”.)

HASTELLOY® alloys of the Ni-Mo, Ni-Cr-Mo and Ni-Cr-Mo-W types. Table 1.1 provides a timeline of major alloy developments over the last century.(5–7)

As exploration and mining technology improved, the supply of nickel and copper largely exceeded the demand. The onset of World War I brought about the need for ballistic steels for defense against high energy projectiles. Demand for nickel increased during the war because it was the key element that induced the hardness and toughness in these special military-oriented steels. Following World War I, the demand for nickel again languished and INCO, in a visionary moment in 1922, created the Huntington Works in Huntington, West Virginia, whose charter included the development of useful new nickel alloys and their introduction to the marketplace. The locale of Huntington, West Virginia was chosen because of three important characteristics:

- 1) there was an abundance of low-sulfur natural gas that would be needed for melting, annealing, and heat treating;



Figure 1.3 Photo of Elwood Haynes.

- 2) Huntington is situated near the confluence of the Guyandotte and Ohio rivers both of which were navigable; and
- 3) the Huntington area was populated with a ready supply of low-wage inhabitants who tilled the land and could readily be trained as mill workers.

Additionally, a rail system already served the city of Huntington, which was named for the railroad magnate Collis P. Huntington.

In 1922, INCO authorized the expenditure of \$3,000,000 (approximately \$40,000,000 in 2008 dollars) to build a research and development facility, and rolling mill on the east bank of the Guyandotte River in West Virginia, and the Huntington Works of INCO came into being.(8) Initially, inconsequential markets such as laundry services, and domestic and commercial kitchen sinks were fabricated using MONELL metal, as it was called initially. Later, the name was changed to MONEL[®] because the U.S. Patent office would not issue a patent that contained a personal name. The alloy was chosen because of its stainless, non-rusting nature before the commercial use of stainless steels began. The facility at Huntington became the primary production facility for

TABLE 1.1 Timeline showing the development of many Ni-base alloys.

Time Period	Alloys
1900–1909	MONEL ¹ alloy 400, Ni-Cr alloys.
1910–1919	HAYNES ² alloy 6B.
1920–1929	MONEL alloy K-500, HASTELLOY A, HASTELLOY B.
1930–1939	INCONEL alloy 600, MONEL alloy R-405, PERMANICKEL alloy 300, HASTELLOY C, and HASTELLOY D.
1940–1949	INCONEL alloy X-750, INCOLOY alloy 800, INCOLOY alloy 801, DURANICKEL alloy 301, HAYNES STELLITE alloy 21, HAYNES STELLITE alloy 31, NI-SPAN-C alloy 902, NIMONIC alloy 75, NIMONIC alloy 80, NIMONIC alloy 80A, NIMONIC alloy 90, and HAYNES alloy 25.
1950–1959	INCONEL alloy 751, INCOLOY alloy 825, HASTELLOY X, NIMONIC alloy 105, NIMONIC alloy 108, PE 11, and PE 16.
1960–1969	INCONEL alloy 718, INCONEL alloy 690, INCONEL alloy 625, INCOLOY alloy 840, NIMONIC alloy 81, HASTELLOY C-276, and HAYNES 188.
1970–1979	INCONEL alloy 601, INCONEL alloy 617, INCONEL alloy MA 754, INCONEL alloy 706, INCOLOY alloy 800H, INCOLOY alloy 903, INCOLOY alloy MA 956, UDIMET alloy 720, NIMONIC alloy 101, NIMONIC alloy 86, HASTELLOY B-2, and HASTELLOY C-4.
1980–1989	INCONEL alloy 601GC, INCONEL alloy 625LCF, INCONEL alloy 725, INCOLOY alloy 925, INCOLOY alloy 800HT, INCOLOY alloy 907, INCOLOY alloy 908, INCOLOY alloy 909, ALLCOR ³ , HASTELLOY C-22, HASTELLOY G-30, and HASTELLOY C-2000.
1990–1999	INCONEL alloy 622, INCONEL alloy 686, INCONEL alloy 783, INCONEL alloy 718SPF, INCOLOY alloy 890, NILO alloy 365, NILO Filler Metal CF36, INCOLOY alloy 864, INCOLOY alloy 832, NI-ROD Filler Metal 44HT, VDM ⁴ 59, VDM B-4, and HASTELLOY B3.
2000+	HASTELLOY G-35, HAYNES 282, INCONEL alloy 693, HASTELLOY C-2000, INCONEL Filler Metal 52M, INCONEL alloy 740, INCONEL alloy TD, and INCOLOY alloy 27-7Mo.

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²The following are registered trademarks of Hayes International: HAYNES, HASTELLOY, HAYNES STELLITE.

³ALLCOR is a registered trademark of Allegheny Ludlum-ATI.

⁴VDM is a registered trademark of VDM Alloys of Germany.

wrought nickel alloys and the primary location for INCO's nickel alloy research.

Shortly after the establishment of the Huntington Works, a foundry and the early beginnings of a welding research facility were established in Bayonne, N.J. From the 1930s to the 1950s, the atomic hydrogen and the oxy-fuel welding

processes were used extensively, and the nickel alloy base metals were used as welding consumables when drawn to welding wire. With the advent of “Heliarc” welding (now known as the gas-tungsten arc welding, GTAW) and the gas-metal arc welding (GMAW) processes, improved welding consumable alloy compositions were required in order to avoid the tendency for porosity and cracking imposed by the faster heating and cooling cycles of the new processes. Typically, aluminum and titanium were added to control oxygen and nitrogen contamination from the atmosphere and niobium and titanium were useful initially for cracking resistance.

During the first half of the twentieth century, companies including Sherritt-Gordon and Falconbridge established nickel mining and refining operations, and Henry Wiggin and Co. Ltd. in the United Kingdom (UK) and Haynes Alloys in Kokomo, Indiana started nickel alloy research and production facilities. The Henry Wiggin Co. first initiated and then worked closely with the Rolls Royce Co. to develop the NIMONIC[®] family of nickel-chromium alloys. Haynes Alloys also began to develop commercial alloys under the HASTELLOY[®] trademark. Other nickel alloy producers were formed in Europe and the Asia Pacific, but alloy development generally lagged that of the USA and UK.

In the 1920s and 1930s, market demands for higher strength Ni-base alloys drove the research of INCO physicist, Paul D. Merica to conceive of and then to develop precipitation-hardening nickel alloys.(6,9) From the early days of Monell, the metallurgy of nickel alloys was relatively unknown except that the basic structure was austenitic, and therefore the matrix arranged itself in the face-centered-cubic structure as it solidified. In fact, it became known that nickel was the most effective and useful austenite stabilizer in most of the early alloys being developed. The demands of early marine, naval, and oil and gas applications for higher strength combined with corrosion resistance prompted the research that resulted in the addition of aluminum and titanium to Ni-Cu alloys to produce a much stronger version of the 70Ni-30Cu alloy that would form a second phase when properly heat treated.(10) The second phase became known as gamma prime (γ'). This precipitation strengthened Ni-Cu alloy became known as K-MONEL[®] and later MONEL[®] alloy K-500. When precipitation-hardened by heat treatment, the alloy nearly doubles in tensile and yield strength relative to standard Alloy 400 due to the formation of γ' .

The ability to significantly increase the strength of Ni-base alloys by precipitation-hardening became one of the most transformational technical discoveries of the nickel alloy industry in the twentieth century. Due to the remarkable increase in strength-to-weight ratio made possible by the precipitation-hardening alloys, the aerospace industry was literally thrust into the age of jet propulsion since the weight of turbine engines could be reduced significantly. The later development of INCONEL[®] alloy 718 further advanced the development of gas-turbine jet propelled aircraft. The precipitation-hardening effect made possible by the formation of gamma prime will be

discussed in detail in Chapters 2 and 4. With the introduction of precipitation-hardened MONEL[®] K-500, many new applications for Ni-base alloys evolved such as non-magnetic drill collars that were used for directional control during oil well drilling, and large Navy marine propeller shafts with excellent torsional strength and salt-water corrosion resistance. Other high-strength nickel alloys of the times included INCONEL[®] alloy X-750.

While not strictly associated with nickel alloy development, other transformational discoveries for the use of nickel were realized in the iron foundry industry. These included the development of the NI-HARD[®] family^{vii} of Fe-based grinding and crushing alloys and ductile iron that used the master alloy Ni-Mg to inoculate the bath of iron with magnesium to precipitate spheroidal graphite particles instead of flakes. These developments span the 1930s through the late 1940s.

The next dramatic application of Ni-base alloy technology was the development of nuclear power plants for electricity generation. At the forefront of the construction of commercial nuclear power plants was INCONEL[®] alloy 600. It was selected due to its record of excellent corrosion resistance in aqueous environments and it was used extensively from the late 1950s through the late 1970s, during the worldwide construction boom of nuclear power plants. It was later learned that the alloy was susceptible to stress-corrosion cracking in the nuclear primary water environment. This discovery spawned the development of alloys and welding consumables containing 30% chromium for resistance to stress-corrosion cracking.

The role of nickel and Ni-base alloys in technological developments over the past 100 years are well-documented. From the time it was named by Cronstedt in the late eighteenth century to the present, milestone uses and alloy developments have allowed tremendous progress in many industries that would not have been possible with other alloy systems. Although initially found to be difficult to refine and separate, nickel has become the unique and nearly universal acceptor as the solvent element in many modern alloys and welding products. Because of its near total immunity for forming compounds with carbon, (it is only known to form nickel carbonyl, a highly toxic gas) its metallurgy and weldability issues are considerably simpler than those of iron-based materials. As the reader of this text will find, the mysteries of the metallurgy of nickel and the difficult problems associated with weldability have been addressed successfully on most fronts.

1.3 CORROSION RESISTANCE

The range of Ni-base alloys available today is expansive and one can be chosen for nearly any type of corrosion-resisting application. The commercially-pure nickel alloys 200 and 201 find application in the production and processing of

^{vii}NI-HARD is a registered trademark of Special Metals, a PCC Company.

caustics such as NaOH and KOH. These alloys are chosen in the production and processing of caustics because nickel is the key alloying element that imparts resistance to stress-corrosion-cracking in pure caustic. Additionally, alloys that contain at least 42% nickel are virtually immune to chloride ion stress-corrosion-cracking, the bane of the austenitic stainless steels. The precipitation-hardening pure nickel alloys 300 and 301 find use for their high strength and high thermal conductivity in glass molds and as thermal spray alloys. The nickel-copper alloys are often used in seawater and for salt production, as well as in general acid-resisting applications. As increasing amounts of copper are added to nickel, the resistance of the alloy to reducing acids is enhanced, but neither nickel nor copper provide resistance to oxidation nor to oxidizing acids.

The precipitation-hardening Ni-Cu alloys K-500 and K-501 find use in high torsional stiffness shafting, and general and marine corrosion resisting service. The Ni-Cr alloys containing iron, cobalt, and aluminum find use at temperatures up to 1150°C (2100°F) due to excellent oxidation-resistance and creep strength. Some specially formulated nickel alloys provide useful oxidation and sulfidation resistance to 1260°C (2300°F) but cannot contain the solid-solution-strengthener, molybdenum. There is a family of Ni-Cr-Co-Mo alloys that are limited in application to 1177°C (2150°F) because of the tendency for molybdenum to ablate or sublime catastrophically above this temperature. The precipitation hardening versions of these alloys are relied upon heavily for both land-based and aerospace gas turbine uses up to about 760°C (1400°F). Other Ni-Cr alloys containing Mo and W are extremely resistant to pitting and crevice corrosion. These alloys make use of the protection against reducing acids of molybdenum and tungsten while relying on chromium to impart resistance to oxidizing species. These alloys are quite useful when a variety of acidic conditions exist or may be encountered such as in flue gas desulfurization service. The simple Ni-Mo alloys are used for a wide range of concentrations of hydrochloric acid.

The solid-solution strengthened Ni-Fe-Cr alloys are mainly used for medium to high temperature thermal processing and hydrocarbon processing in creep-resisting temperature regimes. There are also a number of precipitation-hardening Ni-Fe and Ni-Fe-Cr alloys used for high strength, controlled expansion applications.

1.4 NICKEL ALLOY PRODUCTION

Currently, there are numerous nickel alloy production facilities throughout the world. There are at least five major mills in the USA along with multiple mills in South America, Germany, France, the United Kingdom, Japan, China, Italy and Spain. Melting methods used for nickel alloys range from simple air induction melting (AIM) to complex triple melt processes called for by some gas turbine rotating parts specifications. Triple melting normally involves a combination of vacuum induction melting (VIM), electroslag remelting (ESR) and

vacuum arc remelting (VAR). The triple melt process is often used to produce “superalloys” that require exceptionally low impurity levels for combined high-strength and high-temperature fatigue properties.

Other melting methods used are electric arc furnace (EAF) melting followed by argon-oxygen-decarburization (AOD), pressurized ESR, and combined VIM/VAR. The AOD process allows the careful control of carbon while protecting against chromium loss due to the presence of argon in the decarburizing gas injected into the molten bath. The pressurized ESR process allows the introduction of nitrogen into the melt of iron-containing stainless steels for the production of alloys resistant to pitting and crevice corrosion. The vacuum-augmented melting methods (such as VIM/VAR) are employed to eliminate gases such as oxygen and nitrogen, thereby reducing oxides and nitrides to very low levels. ESR is capable of reducing sulfur and other elements that can be removed by fluxing reaction of the slag.

Once melting has been completed, processing to various mill forms such as plate, sheet, bar, and wire are accomplished by a series of conventional hot-working and cold working operations with annealing operations applied as necessary. Continuous casting has found little use for production of nickel alloys primarily because of the specialty nature of most nickel alloys which limits the use of large melts and continuous runs of the same alloy. Thus conventionally cast ingots are produced from the above melting processes. Flux casting and bottom-pouring are improvements that have been introduced as quality demands continue to increase. From the ingot stage, there may be an overhaul step or in some cases the final melt process may provide a suitable surface for hot break-down of the ingot.

Some alloys require a high-temperature homogenization before break-down, while others can be directly rolled or forged from the preheating furnace. The breakdown is usually applied to multiple pieces of smaller cross-section called billets or blooms. These are, in turn, reduced to either finished or semi-finished product forms. Most finished product forms are produced using a combination of hot and cold rolling with annealing, blasting, and pickling, but seamless tubing and some shapes are produced by hot extrusion and further cold working. As product section thickness is reduced, bright annealing with hydrogen is sometimes used to produce clean, smooth surfaces of final products without the use of chemical pickling.

During the various cold working processes such as rolling or drawing, the nickel alloys exhibit a work hardening rate characteristic of each alloy. The work hardening rate is typically higher for the more complex alloys (high alloy content) and with increasing carbon content. The simple alloys such as commercially pure nickel can sometimes be rolled or drawn without an intermediate annealing step, but in contrast, most of the nickel alloys require intermediate annealing to induce recrystallization and softening for further reductions in section.

Nickel alloy welding products are principally produced by the cold-drawing process and it is not unusual for multiple draws and anneals to be used to

produce the desired diameter and properties. Surface conditioning during working and for final production is critical for making welding consumables that are easy to use and that produce clean, strong ductile welds. More information on welding consumables utilized for the various types of Ni-base alloys can be found in subsequent chapters.

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