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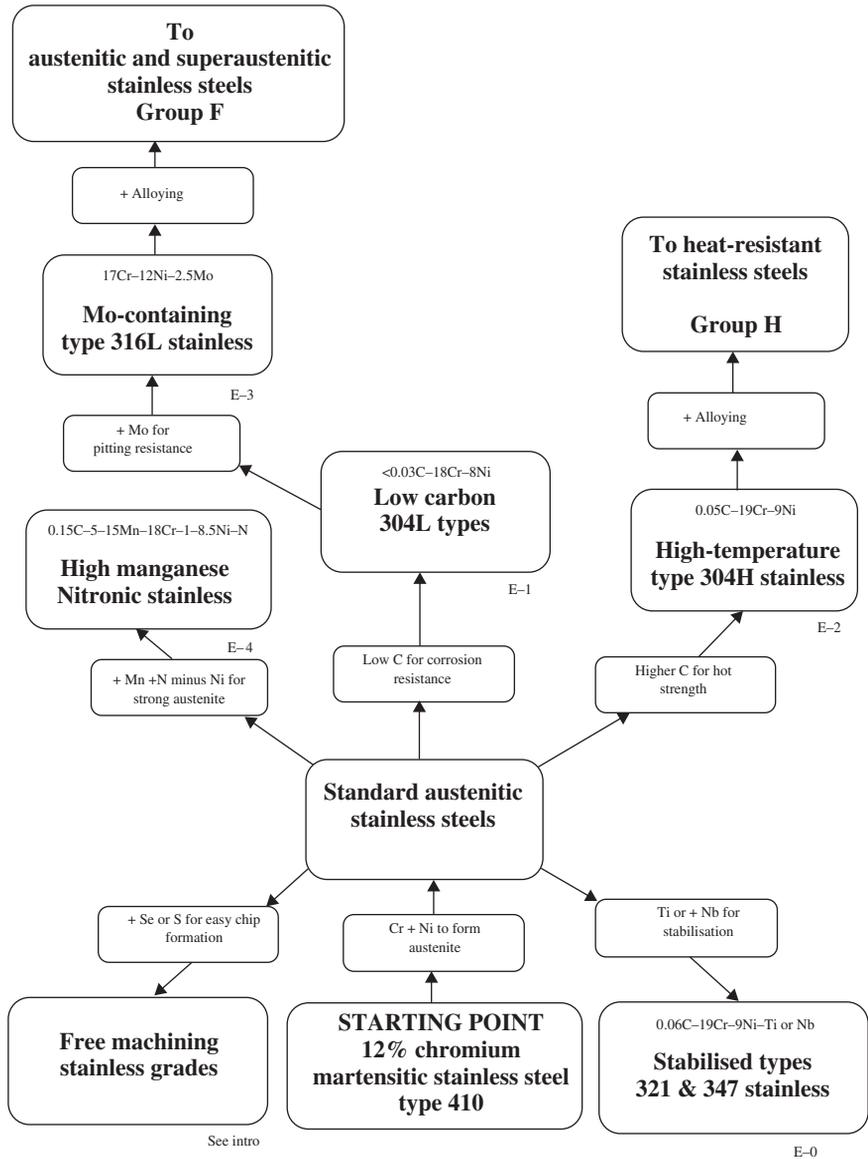
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Group E

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# **Standard austenitic stainless steels**



Group E: Standard austenitic stainless steels.

# Introduction

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Group E is at the heart of the alloy tree. The starting point, as for Group D, is the 12% chromium, type 410 martensitic stainless steel, but unlike Group D, this group has a number of highly significant side branches.

The centre of this group is a standard austenitic stainless steel, which evolved from the 12% chromium martensitic steel into a fully austenitic steel through the addition of chromium and the introduction of nickel. There is no individual data sheet for this generic austenitic stainless steel. The reason for this is that the most widely used stainless steels are either low carbon for weldability, or controlled carbon for elevated temperature properties and these two specific types are shown separately and have individual data sheets. Two branches illustrate this fundamental difference. The first of these, on the middle/upper-left hand side, takes the low-carbon route and also introduces molybdenum for improved corrosion resistance before leading to Group F, austenitic and superaustenitic stainless steels. The second branch, on the right hand side, takes the controlled carbon route and leads to Group H, heat-resistant stainless steels.

There are three other branches. The first of these shows the effect of adding titanium or niobium to provide stabilisation.

The second demonstrates the role of manganese as an austenite former and its importance as a substitute for nickel in a specific group of austenitic stainless steels.

Finally, there is a third branch which shows that sulphur or selenium is often used to produce free-cutting or free-machining grades of various types of stainless steels, particularly austenitic types. Austenite is particularly tough and rapidly work hardens. For this reason, machining of components can be slow, lead to a poor surface finish and rapid tool wear. It is possible to improve machinability by introducing either sulphur or selenium at levels up to about 0.3%. This is at least 10 times the level that would normally be found in a standard grade of stainless steel. The sulphide films formed in the alloy reduce the local ductility and so assist 'chip breaking', with a consequent improvement in machinability. Selenium is more efficient than sulphur, but tends to be used only in more expensive stainless steels because of its higher cost. The disadvantage of free-cutting steels is the detrimental effect of the sulphur or selenium on weldability. Both these elements tend to promote weld metal and/or HAZ hot cracking and to avoid this, special precautions must be taken. The use of sulphur or selenium is not specific to any particular grade of stainless steel and no specific data sheet has been produced.

## E-0

### 18% chromium, 8% nickel austenitic stainless steels, stabilised with titanium or niobium

Also known generically as types 321 and 347

#### Description

These steels are '18/8' grade (18% chromium, 8% nickel) with additions of either titanium or niobium to stabilise the carbon content. The additions of titanium or niobium are usually specified as being a minimum of about ten times the carbon content. Therefore, a carbon content of 0.06% would typically require a stabilisation level of about 0.7%. A typical composition is:

	C	Mn	Si	S	P	Cr	Ni	Ti or Nb
Weight %	~0.06	2	0.5	<0.01	<0.02	19	9	0.7

The steels are normally supplied in accordance within one of the following specifications:

UNS	ASTM	EN
S32100	Gr. 321	1.4541
S34700	Gr. 347	1.4543/1.4561/1.4550
	Gr. CF8C (cast)	1.4552 (cast)

The steels are always solution treated followed by quenching to give a fully austenitic structure.

#### Background

Until about 1970, the standard grades of 304 types had relatively high carbon levels sometimes up to the specification limit of 0.08%. Low-carbon grades were much more difficult to produce and commanded a premium price. This became a problem, since stainless steels were increasingly being used in chemical plant and needed to be fabricated using welding. The high temperatures reached in the weld HAZ caused chromium carbides to form, which resulted in localised depletion of chromium content and a corresponding reduction in intergranular corrosion resistance. This phenomenon was known as weld decay. The stabilised grades were developed to overcome

this problem by additions of titanium or niobium. These strong carbide formers combine preferentially with the carbon, leaving the chromium at the level required to maintain corrosion resistance.

## **Performance**

These steels tend to be used for their 'stainlessness' rather than their mechanical properties. The austenitic structure is relatively weak and soft unless it is deliberately strengthened by nitrogen additions or by work hardening. However, austenite is tough over a wide range of temperatures and does not show any transitional behaviour. These steels therefore have useful cryogenic properties. Although they will resist scaling at high temperatures because of their relatively high chromium content, they are not generally intended for service above about 450 °C unless the carbon content is deliberately controlled to above 0.05%.

## **Applications**

The main applications for types 321 and 347 stainless steels are those where sterility and appearance are important rather than high corrosion resistance. They were once widely used in food, drink and pharmaceutical production, and processing where exposure tends to be restricted to weak acids. Particularly large users were the brewing and wine industries, where the ability to maintain cleanliness ensures consistency of production and minimum waste. However, with the ready availability of very low-carbon grades of stainless steels, which are immune to weld decay (E-1), the use of the stabilised grades fell substantially towards the end of the 20th century.

Those grades designated 321H and 347H, with carbon in excess of 0.05%, can be used for some higher-temperature applications (>500 °C) in the petrochemical, power generation and nuclear industries. However, as more advanced materials have become available, their use even in these rather specialised sectors has diminished.

# E-1

## 18% chromium, 8% nickel low-carbon austenitic stainless steel

Also known generically as type 304/304L

### Description

This steel is the ubiquitous '18/8' grade with low carbon, 18% chromium and 8% nickel. The addition of about 6% chromium to the standard 12% chromium, type 410 composition, together with the microstructural balancing effect of the nickel, gives rise to a stable austenite structure and some improvements in corrosion resistance. A typical composition is:

	C	Mn	Si	S	P	Cr	Ni
Weight %	<0.03	2	0.5	<0.01	<0.02	19	9

The steels are normally supplied in accordance within one of the following specifications:

UNS	ASTM	EN
S30403	Gr. 304L	1.4306
S30400	Gr. 304	1.4301
S30453	Gr. 304LN	1.4311
	Gr. CF3 (cast)	1.4308
	Gr. CF8 (cast)	

The steels are always solution treated followed by quenching to give a fully austenitic structure.

### Background

Until the 1970s, the standard 304 grades had relatively high carbon levels, sometimes up to the specification limit of 0.08%. Low-carbon grades were much more difficult to produce and commanded a premium price. However, the widespread introduction of argon–oxygen decarburisation (AOD) meant that low-carbon stainless steels could be economically produced in large tonnages. The low-carbon grades have now become standard, with significant improvements in weldability and the virtual

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elimination of weld decay caused by carbide formation and chromium depletion in the weld HAZ.

## **Performance**

These steels tend to be used for their 'stainlessness' rather than their mechanical properties. The austenitic structure is relatively weak and soft unless it is deliberately strengthened by nitrogen additions (304LN) or by work hardening. However, austenite is tough over a wide range of temperatures and does not show any transitional behaviour. These steels therefore have useful cryogenic properties. Although they will resist scaling at high temperatures because of their relatively high chromium content, they are not intended for service above about 450 °C. Above this temperature, 304H (H-3) should be considered.

## **Applications**

The main applications for 304L type stainless steels are those where sterility and appearance are important rather than high corrosion resistance. They are widely used in food, drink and pharmaceutical production, and processing where exposure tends to be restricted to weak acids. Particularly large users are the brewing and wine industries, where the ability to maintain cleanliness ensures consistency of production and minimum waste. Use in medical, food preparation and the domestic environment is well known.

One exception to the above is the use of a special low-residuals grade known as 'nitric acid grade' or NAG. This grade has been used extensively in the construction of nuclear fuel reprocessing facilities, which handle nitric acid during the fuel dissolving and processing operations.

As the price relative to other grades of steel has decreased over the last 25 years, there has been a major growth in its use for building cladding and other architectural features. However, their external use should be restricted to clean urban and suburban environments. Type 304L will tarnish and corrode by pitting when exposed to polluted industrial and marine or salt-contaminated atmospheres.

## E-2

### 18% chromium, 8% nickel austenitic stainless steel with controlled carbon content

Also known generically as type 304H

#### Description

This steel is the same as ubiquitous type 304L with the exception that it has a higher controlled carbon content and is specifically designed for high-temperature operation. A typical composition is:

	C	Mn	Si	S	P	Cr	Ni
Weight %	0.04-0.08	2	0.5	<0.01	<0.02	19	9

The steel is normally supplied in accordance within one of the following specifications:

UNS	ASTM	EN
S30409	Gr. 304H Gr. CF8 (cast) Gr. CF10 (cast)	1.4948

These steels are always solution treated followed by quenching to give a fully austenitic structure.

#### Background

Now that the standard grades of type 304 are all essentially low-carbon, or even extra low-carbon, grades, it is necessary to produce grades with the carefully controlled carbon contents required to give long-term high-temperature performance.

#### Performance

These steels tend to be used for their high-temperature scaling resistance and long-term thermal stability and creep rupture strength rather than their corrosion resistance. In fact their corrosion resistance is not particularly good and precautions have to be taken to avoid corrosive acid condensates,

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which form at low temperatures during shut down of catalytic cracking processes and may cause pitting attack.

## **Applications**

The main application for 304H type stainless steels is in petrochemical and chemical process plant operating at relatively high temperatures. They are widely used in the construction of parts of oil refinery catalytic crackers (cat crackers), which produce light gasoline and diesel fuels from heavier residues remaining from the primary distillation process. These plants operate continuously for long periods and therefore reliability of material performance is essential. Items made from 304H include catalyst recovery cyclones, hot gas and catalyst transfer lines, and support grids.

This grade of stainless steel has also been used to fabricate silencers for jet engine testing rigs where the steel has to withstand the eroding effects of the high-temperature exhaust gases.

## E-3

### 17% chromium, 12% nickel, 2.5% molybdenum austenitic stainless steel

Also known generically as type 316/316L

#### Description

This steel is the most widely used grade of stainless steel with low carbon, 17% chromium, 12% nickel and 2–3% molybdenum. The addition of the molybdenum improves the corrosion properties, particularly the pitting resistance when compared with type 304/304L. Molybdenum is a ferrite former and therefore the nickel content has to be increased somewhat to maintain a stable austenitic structure. A typical composition is:

	C	Mn	Si	S	P	Cr	Ni	Mo
Weight %	<0.03	2	0.5	<0.01	<0.02	17	12	2.5

The steel is normally supplied in accordance within one of the following specifications:

UNS	ASTM	EN
S31603	Gr. 316L	1.4404/1.4401
S31600	Gr. 316	1.4436
S31653	Gr. 316LN	1.4406/1.4429
	Gr. CF3M (cast)	1.4408
	Gr. CF8M (cast)	1.4437

This steel is always solution treated followed by quenching to give a fully austenitic structure.

#### Background

Until about 30 years ago the standard grades had relatively high carbon levels up to the specification limit of 0.08%. Low-carbon grades were much more difficult to produce and commanded a premium price. However, the widespread introduction of AOD meant that low-carbon stainless steels could be economically produced in large tonnages. The low-carbon grades have now become standard with significant improvements in weldability

and the virtual elimination of weld decay caused by carbide formation and chromium depletion in the weld HAZ. The addition of 2–3% molybdenum has a dramatic effect on corrosion resistance, particularly pitting resistance in salt environments, when compared with type 304L.

## **Performance**

These steels tend to be used for their ‘stainlessness’ rather than their mechanical properties. The effect of the molybdenum is to increase the PRE value by about 8 from about 18 for 304L to 26 for 316L. The austenitic structure is relatively weak and soft unless it is deliberately strengthened by nitrogen additions (316LN) or by work hardening. However, austenite is tough over a wide range of temperatures and does not show any transitional behaviour; therefore these steels have useful cryogenic properties.

Although they will resist scaling at high temperatures because of their relatively high chromium content, they are not intended for service above about 450 °C, and in some circumstances the molybdenum can give rise to catastrophic oxidation.

## **Applications**

Type 316L stainless steels take over from type 304L when corrosion conditions become more aggressive or there is a risk of pitting attack from chloride environments. They are used in a wide range of chemical and petrochemical process plants and are reasonably resistant to dilute acids at fairly low temperatures. Austenitic stainless steels are sensitive to chloride-induced SCC when residual stresses are present and temperatures are within the critical range (above about 65 °C).

As with type 304L, their use in buildings is increasing, particularly in polluted or marine environments. A particularly successful application has been the external cladding of offshore oil and gas platform modules, where significant savings in maintenance and repainting costs have been achieved.

## E-4

### Austenitic stainless steels with high manganese and nitrogen

Also known generically as Nitronics

#### Description

Both manganese and nitrogen are austenite stabilisers in stainless steels and can be used together as a direct substitute for nickel or to produce useful properties in their own right. This data sheet provides a brief outline of this family of steels and gives details of two of the more commonly used grades. (The high-temperature alloy Esshete 1250, with about 6% Mn, could be included in this group but, as a high-temperature alloy, is described separately in H-1.) Typical compositions are:

		C	Mn	Si	S	P	Cr	Ni	Mo	N
Weight %	<b>Grade 216L</b>	>0.03	8.5	0.5	<0.01	<0.02	19	6	2.5	0.35
	<b>Nitronic 60</b>	0.05	8	4	<0.01	<0.02	17	8.5	-	0.15

The steels are normally supplied in accordance with one of the following specifications:

	UNS	ASTM
<b>Grade 216L</b>	S21603	Gr. 216L
<b>Nitronic 60</b>	S21800	Gr. 218

These steels are solution treated followed by quenching to give a fully austenitic structure.

#### Background

High-manganese, high-nitrogen stainless steels were developed in the early part of the 20th century and have a wide range of useful properties for certain applications. However, in periods of nickel shortages and high prices, they assume an extra importance. The alloys fall into two groups: those such as grade 216L, which are used as direct substitutes for the standard austenitic stainless steels, such as 316L, and those such as Nitronic 60 which offer properties over and above the standard grades. Many of the alloys are

proprietary and include minor alloying additions designed for rather specific applications. Much of the development and exploitation has taken place within the USA, particularly by the Armco Steel Corp., which used the term Nitronic as a trade name for this group of steels.

## **Performance**

These steels tend to be used for their economy, 'stainlessness' and mechanical properties.

Low-carbon grades such as 201 and 202, where about half the nickel is replaced by manganese, have similar corrosion and mechanical properties to type 304L (E-1) stainless steels. However, grades combining high manganese levels with nitrogen, but maintaining nickel and molybdenum contents, offer corrosion resistance superior to type 316 (E-3) with much improved strength. Grades such as Nitronic 60 combine high manganese with high silicon contents and offer excellent resistance to galling.

Some of these benefits have been overtaken by the introduction of duplex stainless steels and most nitronic alloys are now used because of their cryogenic properties, their non-magnetic properties or their very high resistance to wear and galling, particularly in metal-to-metal contact.

## **Applications**

The applications for Nitronic types are many and diverse. Large quantities have been used in the past in the USA for the construction of rail passenger cars as a cost-effective alternative to 304L.

A major application, also in the USA, has been in the manufacture of spent nuclear fuel storage containers. Considerations were corrosion resistance in underwater ponds combined with high strength and consequent weight saving. Parts of the assembly subject to metal-to-metal contact were made from an anti-galling grade.

They are also used for cryogenic, liquid gas storage tanks, where the tough high-strength austenitic structure offers very real advantages over other highly alloyed steels or duplex alloys that have comparatively poor toughness at temperatures below about  $-50^{\circ}\text{C}$ .

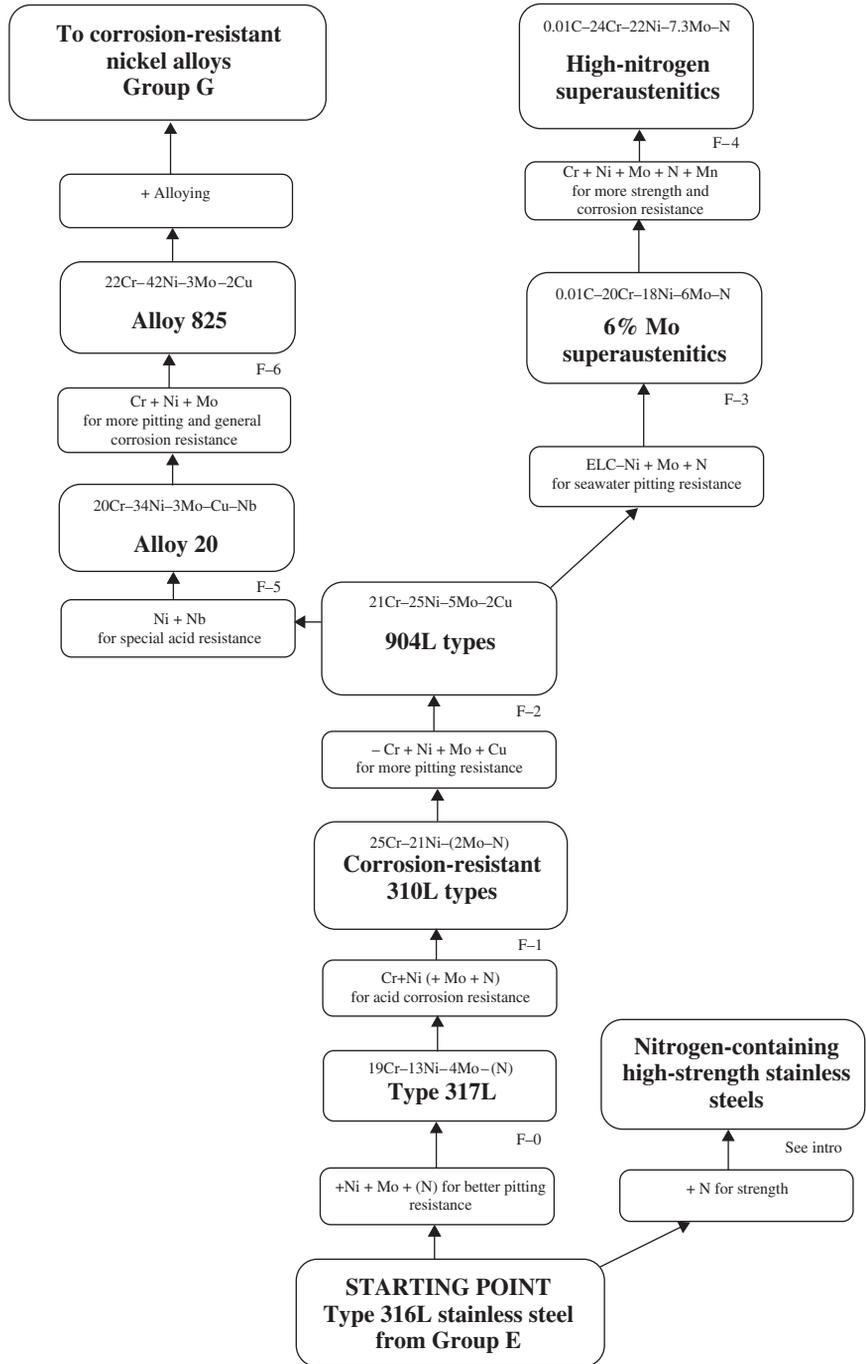
Finally, they are widely used for a wide range of corrosion and galling-resistant, machined components, including automotive exhaust valves.



Group F

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# **Austenitic and superaustenitic stainless steels**



Group F: Austenitic and superaustenitic stainless steels.

# Introduction

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Group F starts with type 316L from Group E and shows how increases in chromium, nickel and, in some cases, molybdenum lead to fully austenitic steels such as type 904L, with much improved corrosion resistance. At this point the group splits into two distinct branches. The left-hand branch represents what might be described as the traditional route to further improvements in corrosion resistance. This was historically achieved by yet greater increases in alloy content until such point that the distinction between high-alloy austenitic stainless steels and nickel alloys becomes blurred. This point is represented by alloy 825 which then becomes the starting point for Group G corrosion-resistant nickel alloys.

The right hand branch illustrates the evolution of the modern generation of superaustenitic stainless steels, which have used a combination of high-nitrogen and high-molybdenum contents to achieve enhanced pitting and crevice corrosion resistance. In a way, the development of superaustenitic alloys mirrored that of superduplex alloys and occurred over much the same period of time. The highest alloyed superaustenitic stainless steels, as with some superduplex types, probably represent the limit of development. Further improvements in corrosion resistance can be achieved only by the use of nickel alloys, where higher levels of critical elements such as molybdenum can be accommodated.

Also included in this group are standard austenitic steels, which are strengthened by the addition of nitrogen. Nitrogen is an austenite former and provides significant matrix strengthening at levels of about 0.15% compared with 0.05% in the standard grades. This is a very economical method of increasing strength and is applied to a number of standard austenitic stainless such 304L and 316L. The specifications show minimum yield strengths increasing by about 30%, but because the 304L grade comfortably exceeds the specification minimum, the actual nitrogen strengthening effect is only about 15%. No individual data sheets are given for these alloys, because they are simple modifications to standard grades.

## F-0

### 19% chromium, 13% nickel, 3.5% molybdenum, austenitic stainless steel

Also known generically as type 317L

#### Description

This steel is somewhat more highly alloyed than type 316L with increases in nickel to 13% and molybdenum to about 3.5%. This gives an overall improvement in corrosion resistance and in particular pitting resistance.

Further improvements are achieved in a modified grade known as type 317LMN, which contains molybdenum at the 4.5% level as well as nitrogen at about 0.15%.

Both grades have higher nickel levels in order to maintain a fully austenitic structure and in this respect the nitrogen in 317LMN also acts a strong austenite former. Typical compositions are:

		C	Mn	Si	S	P	Cr	Ni	Mo	N
Weight %	Type 317L	<0.03	2	1	<0.01	<0.02	19	13	3.5	-
	Type 317LMN	<0.03	2	0.75	<0.01	<0.02	19	15	4.5	0.15

The steels are normally supplied in accordance within one of the following specifications:

UNS	ASTM	EN
S31703	Gr. 317L	1.4434
S31725	Gr. CG8M	1.4438
S31726	Gr. 317LMN	1.4439

These steels are always solution treated followed by quenching to give a stable fully austenitic structure. This is particularly the case with 317LMN, which, because of its higher molybdenum content, has a greater tendency to form sigma, etc.

#### Background

These steels are intended to be welded and to maintain good corrosion resistance and are invariably supplied in the low-carbon form with carbon levels of well below 0.03%.

They represent an intermediate grade between the very widely used type 316L grade and the more costly, more modern, so-called 'superaustenitic' grades (F-2 and F-3). In this respect the type 317LMN with a molybdenum content of 4.5% and some nitrogen additions effectively represents a midway point between the standard austenitic grades with about 3% molybdenum and no nitrogen additions, and the more recently developed 6% molybdenum superaustenitic stainless steels, which have significant amounts of nitrogen alloying.

## **Performance**

These alloys are designed to have better general and pitting corrosion resistance than type 316L, combined with a modest cost premium. For type 317L the increase in PRE value over type 316L is about 5, whereas for type 317LMN it is a further 6 to give a total value of about 35. This is similar to standard 22% chromium duplex stainless steels (D-1).

In terms of mechanical properties, these steels are somewhat stronger than type 316L because of the increased molybdenum content and, in the case of 317LMN, the nitrogen additions.

## **Applications**

In the past, type 317 steels were quite widely used when corrosion conditions were too aggressive for type 316L. However, more modern duplex and superaustenitic stainless steels have largely displaced them. They are still used in certain marine environments and in general construction and building where atmospheric conditions cause pitting and staining of 316L. They are reasonably resistant to acids, except nitric acid, and have been exploited widely in chemical plant, pulp and paper plant and food processing. For a time they were used for the holding tanks in chemical carriers, but for this application they have in most cases been replaced by stronger duplex stainless steels.

# F-1

## Very low-carbon, 25% chromium, 20% nickel, austenitic stainless steels

Also known generically as type 310L

### Description

These steels are significantly more highly alloyed than type 317L, with a major increase in chromium to 25% and an increase in nickel to 22% or even 25% to maintain a stable, fully austenitic microstructure. The high level of chromium, and the absence of molybdenum, provides good corrosion resistance to strong oxidising acids, particularly nitric acid. The plain 310L grade does not contain molybdenum, but a modified grade, designated 310MoLN, was specifically developed for corrosion resistance in urea plants, and has a modest molybdenum content of about 2% and an addition of some nitrogen. Typical compositions are:

		C	Mn	Si	S	P	Cr	Ni	Mo	N
Weight %	Type 310L	<0.02	2	0.5	<0.01	<0.02	25	21	<0.1	-
	Type 310MoLN	<0.02	2	0.5	<0.01	<0.02	25	22/25	2.2	0.15

The steels are normally supplied in accordance within one of the following specifications:

	UNS	ASTM	EN	Proprietary alloys
310L	-	310L	1.4335	Sandvik 2RE10 Industeel UR65 VDM Cronifer 2521LC
310MoLN	S31050	310MoLN	1.4465 1.4466	Sandvik 3RE69 Industeel 25 22 2 VDM Cronifer 2525LCN

These steels are always solution treated followed by quenching to give a stable fully austenitic structure.

### Background

These steels are intended to be welded and to maintain good corrosion resistance. They are invariably supplied in the very low-carbon form with levels generally below 0.02%.

They represent one part of a family of 25%Cr-20%Ni alloys, all with differing carbon contents; the higher carbon types described in H-4 and H-5, are invariably used for their high-temperature strength and scaling/oxidation resistance, and not for their corrosion resistance. Only these very low-carbon types are used for corrosion-resistant applications.

## **Performance**

The 310L grade has good corrosion resistance in hot strong oxidising acids such as nitric acid. In this respect it is the best stainless steel available and, if higher levels of resistance are required then the use of tantalum, with a very substantial cost penalty, has to be considered.

The 310MoLN, with some molybdenum, nitrogen and additional nickel offers very good resistance to pitting, and intergranular corrosion in both chloride-bearing media and nitric acid.

## **Applications**

These alloys are mainly used in the chemical industry. Type 310MoLN is primarily exploited in the production and processing of urea for fertilisers and sulphuric acid; the steel is fabricated to produce tanks, vessels, pipe work systems and heat exchangers.

Type 310L is used primarily in the production and processing of nitric acid. Many critical items in nitric acid plants, such as heat exchangers and air coolers, are fabricated from this grade of stainless steel. A rather specialised application is the construction of nitric acid dissolver units used in the first stage of spent nuclear fuel reprocessing. Repair and replacement in this highly radioactive environment are time consuming and costly. For this reason, reliable and consistent corrosion resistance is most important.

## F-2

### 21% chromium, 26% nickel, 5% molybdenum, 2% copper austenitic stainless steel

Also known generically as type 904L

#### Description

This steel is significantly more highly alloyed than type 317LMN with a further increase in chromium to 21% and molybdenum to about 4.5%. There is an addition of 1.5% copper which helps to improve corrosion resistance in a range of acids. There are small nitrogen additions in some proprietary variants, but the high level of nickel at about 26% ensures that a stable, fully austenitic microstructure is maintained. This alloy can probably be best described as the forerunner of the family of modern superaustenitic stainless steels. A typical composition is:

		C	Mn	Si	S	P	Cr	Ni	Mo	Cu
Weight %	Type 904L	<0.02	2	1	<0.01	<0.02	21	26	4.5	1.5

The steel is normally supplied in accordance within one of the following specifications:

ASTM/UNS	EN	Proprietary alloys
N08904	1.4505 1.4539	Uddeholme 904L
	1.4506 1.4585	Sandvik 2RK65
	1.4536 1.4500 (cast)	VDM Cronifer 1925LC
		Avesta Polarit 254SLX
		Industeel B6 and B6M

This steel is always solution treated followed by quenching to give a stable fully austenitic structure.

#### Background

This steel is intended to be welded and to maintain good corrosion resistance. It is invariably supplied in the very low carbon form with levels below 0.02%.

It represents the starting point of a series of highly alloyed superaustenitic stainless steels and was developed in the second half of the 20th

century to meet the needs of the rapidly developing chemical, and pulp and paper industries.

## **Performance**

The steel is designed to have much better general and pitting corrosion resistance than type 316L, but at a significant alloy cost premium. In terms of pitting resistance it has a typical PRE value of about 37. However, for many acid environments (not nitric acid), the performance is significantly enhanced by the presence of copper. It offers both good pitting and crevice corrosion resistance in chloride environments.

Although matching welding consumables are readily available and are suitable for most applications, nickel-based weld metals (e.g. alloy 625, see G-0) are usually recommended for service in severe chloride conditions.

## **Applications**

These alloys are still widely used in the chemical and pulp and paper industries, although for some of the more severe applications they have been replaced by modern higher-alloyed grades. Applications include tanks and process vessels, piping systems, agitators, rotors and cast pumps and valves for use in fertiliser, phosphoric, sulphuric and acetic acid plants.

They are also used in seawater environments and have found limited application in offshore oil and gas equipment, sometimes in the form of overlays and cladding on low-alloy steel substrates. Type 904L has also been exploited in flue gas dampers in power station FGD plants where conditions are not usually as aggressive as some other parts where highly acid condensates are present and advanced nickel alloys have to be employed.

## F-3

### 6% molybdenum, nitrogen-alloyed superaustenitic stainless steels

Also known generically as 6% Mo superaustenitics

#### Description

These steels are significantly more highly alloyed than type 317LMN, with an increase in chromium to more than 20% and molybdenum to about 6%. There is a tendency for the high molybdenum level to destabilise the austenite, give rise to segregation, and so reduce corrosion resistance. This effect is counteracted by increasing the nickel content and raising the nitrogen to approximately 0.2%. As with alloy 904L, most grades contain some copper to promote corrosion resistance in acidic media. There is a wide range of proprietary compositions but the most widely used alloys fall within the values given below:

	C	Mn	Si	S	P	Cr	Ni	Mo	Cu	N
Weight %	<0.02	1	0.5	<0.01	<0.02	20/24	18/25	6.5	~1	0.22

The steels are normally supplied in accordance within one of the following specifications:

UNS	ASTM	EN	Proprietary alloys
S31254	CK3McuN (cast)	1.4547	Avesta Polarit 254 SMO
N08925	F44 (wrought)	1.4529	VDM Cronifer 1925hMo
N08367			Allegheny AL-6LX
N08926			Special Metals 25-6Mo

These steels are always solution treated followed by quenching to give a stable fully austenitic microstructure.

#### Background

These alloys are designed for weldability and to maintain good corrosion resistance. They are invariably supplied in the very low-carbon form with levels generally below 0.02%.

They represent an important group of alloys, which were first developed in Scandinavia in the second half of the 20th century to meet increasingly aggressive conditions found in chlorine and chlorine dioxide pulp bleaching plants.

## **Performance**

The steels are designed to have better general pitting and crevice corrosion resistance than types 317LN (F-0) and 904L (F-2). Based on a nitrogen factor of 16, they give PREn values in the range 43 to 45. However, some authorities believe that although this factor is appropriate to duplex stainless steels, a factor of 30 is more appropriate to nitrogen-alloyed superaustenitic steels; if this value is adopted, then the PRE values rise to about 50. Although the nitrogen provides some alloy strengthening, these austenitic steels are inherently weaker than duplex stainless steels of comparable corrosion resistance (Group D). This imposes a weight penalty, particularly in critical applications such as offshore topside modules.

Matching welding consumables are not used for these alloys because of molybdenum segregation in the as-welded condition, and high-alloy corrosion-resistant nickel-based consumables are generally used.

## **Applications**

Superaustenitics are widely used in the chemical and pulp and paper industries, particularly in the more aggressive environments where the risk of general, pitting, crevice and stress corrosion is high. Applications include tanks and digester vessels, piping systems, agitators, rotors and cast pumps and valves. They are also used in seawater environments, particularly fire-water systems and oil and gas process pipework where seawater and hydrogen sulphide contamination is present. Based on service experience in the Scandinavian paper industry, these steels tended to be material of choice for the Norwegian sector of the North Sea oil and gas industry, whereas duplex and superduplex stainless steels were more popular in the UK sector.

## F-4

### Superalloyed, high-nitrogen austenitic stainless steels

Also known generically as high Mo, high N superaustenitics

#### Description

These superaustenitic stainless steels are even more highly alloyed than the 6% molybdenum types and in particular contain nitrogen at the level of about 0.5%. One of the grades contains tungsten rather than a further increase in molybdenum and also about 2% copper for improved acid resistance. Typical compositions are:

		C	Mn	Si	S	P	Cr	Ni	Mo	Cu	W	N
Weight %	<b>654 SMO</b>	<0.02	3	0.5	<0.01	<0.02	24	22	7.5	0.5	-	0.5
	<b>UR B66</b>	<0.02	3	0.5	<0.01	<0.02	24	23	6	~2	2	0.5

The steels are normally supplied in accordance within one of the following proprietary specifications:

UNS	EN	Proprietary alloys
S32654	1.4652	Avesta Polarit 654 SMO
S31266		Industeel UR B66
S34565		

These steels are always solution treated followed by quenching to give a stable fully austenitic structure.

#### Background

These alloys were developed towards the end of the 20th century to bridge the gap between the 6% molybdenum superaustenitic stainless steels and the best, but much more expensive, nickel alloys. They are intended to be welded and to maintain good corrosion resistance and are invariably supplied in the very low-carbon form with levels below 0.02%.

They represent a quite recent development intended to provide corrosion resistance in aggressive situations, particularly where temperatures and pressures have been increased to improve operating efficiencies.

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## Performance

They are designed to have better general, pitting, crevice and stress corrosion resistance than the 6% molybdenum types (F-3). They are claimed to have excellent corrosion resistance in halide-containing solutions, comparable to some nickel alloys.

Based on a nitrogen factor of 16, they give PREn values of about 55, which is about as high as is achievable with stainless steels. If the increased factor for nitrogen of 30 is applied, then the PREn value rises to over 60.

The high nitrogen content provides significant strengthening, and these steels have a 0.2% proof stress that is about 30% higher than the 6% Mo superaustenitics. This makes them comparable in strength to standard 22% Cr duplex alloys and makes them potentially more attractive for weight critical applications.

Matching welding consumables are not used for these alloys because of molybdenum segregation in the as-welded condition. High-alloy corrosion-resistant nickel-based consumables with high molybdenum contents are generally used for welding (see G-3 and G-4).

## Applications

These are new alloys that are being used for those applications where lesser alloys give unsatisfactory performance and the additional costs can be justified. Typical applications include severe crevice corrosion environments such as seawater-cooled plate heat exchangers, flanges in seawater piping systems, bleach plants and power station FGD systems. They are also finding applications in the chemical industry where acid or neutral halide solutions have to be handled and processed.

## F-5

### 20% chromium, 34% nickel, 2.5% molybdenum, 3.5% copper plus niobium, austenitic stainless steel

Also known generically as alloy 20

#### Description

This steel is significantly more highly alloyed than type 904L (F-2), particularly with respect to the nickel, which is increased by about 10%. Molybdenum is somewhat lower at 2.5% but copper is approximately doubled to about 3.5% to improve acid corrosion resistance. Iron is still the majority element at about 40% but this alloy is quite close to the transition point between stainless steels and nickel alloys. A typical composition is:

		C	Mn	Si	S	P	Cr	Ni	Mo	Cu	Nb
Weight %	<b>Alloy 20</b>	<0.05	<2	0.5	<0.01	<0.02	20	34	2.5	3.5	0.5

This alloy is normally produced as castings and supplied in accordance within one of the following specifications:

UNS	ASTM	Proprietary alloys
N08020	Gr CN-7M	Carpenter Alloy 20, 20Cb & 20Cb-3 Lake and Elliot Paramount P20 Meighs Langalloy 20V

This alloy is always solution treated followed by quenching to give a stable fully austenitic structure.

#### Background

This alloy was developed in the USA mid-way through the 20th century to meet the increasing demands of a growing chemical industry, which required improved corrosion resistance, particularly in acid environments. The alloy is generally produced as castings and there has never been a great demand for the wrought version.

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## Performance

The alloy is designed to have much better general corrosion resistance than type 316L, albeit at a significant alloy cost premium. In terms of pitting resistance it is similar to 316L (E-3) with a typical PRE value of about 30. However, it was designed with a high copper content, for high general corrosion resistance in sulphuric acid, other mineral acids, organic acids and their mixtures. It is particularly suitable for handling acid slurries and combines corrosion and reasonable wear resistance when particulate material is present.

Early cast versions were not produced with particularly low carbon contents and some versions of the alloy were stabilised by the addition of niobium at a level of about 10 times the carbon content. This explains the designation 'Alloy 20Cb' (niobium is columbium in the USA).

The alloy is highly austenitic and the presence of niobium increases the risk of hot cracking; this, combined with pick-up of the silicon, which tends to be higher in cast alloys to improve fluidity, means that weld repair of casting defects can be somewhat difficult.

## Applications

This alloy is still used, but not particularly widely because of lack of availability of wrought products and the development of more modern advanced alloys. However, there are some specialised applications where alloy 20 cast valves, pumps and components are still used in acid chemical processes, metal cleaning and metal pickling.

## F-6

### 22% chromium, 42% nickel, 3% molybdenum, 2.5% copper plus titanium, nickel alloy

Also known generically as alloy 825

#### Description

This alloy has a significantly higher nickel content than alloy 20, while retaining both molybdenum and copper for acid resistance. It also contains about 1% titanium, both as an alloy strengthener and to facilitate the production of a wide range of wrought product forms. This alloy is sometimes grouped with the superaustenitic stainless steels, but with a nickel content that exceeds the iron content of about 30%, it is more properly described as a nickel alloy, and for the purposes of this book it is convenient to treat it as the transition alloy between the two groups, namely Groups F and G. A typical composition is:

		C	Mn	Si	S	P	Cr	Ni	Fe	Mo	Cu	Ti
Weight %	<b>Alloy 825</b>	0.02	0.3	0.3	<0.01	<0.02	22	42	30	3	2.5	0.8

This alloy is produced as a range of wrought products and castings and is supplied in accordance within one of the following specifications:

UNS/ASTM	EN	Proprietary alloys
N08825	2.4858	Special Metals Incoloy 825 & 825CP (cast) VDM Microfer 4221

This alloy is always solution treated followed by rapid quenching to give a stable fully nickel-base austenitic structure.

#### Background

This alloy can be considered as a further development of alloy 20 (F-5), although it evolved at about the same time. It was designed with the aim of achieving excellent corrosion resistance in sulphuric and phosphoric acids. The alloy was also produced in a wide range of wrought product forms, which encouraged more widespread exploitation than alloy 20.

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## Performance

Alloy 825 is designed to have much better acid corrosion resistance than alloy 20, particularly in sulphuric and phosphoric acids. It is also reasonably resistant to hydrochloric acids but tends to suffer from chloride pitting and crevice corrosion, particularly in stagnant, unaerated solutions. The relatively high iron content, for a nickel-based alloy, means that it is less resistant to halogens and alkalis than some of the more highly alloyed grades.

The relatively high nickel content does, however, give good resistance to chloride- and hydrogen sulphide-induced SCC, particularly in contaminated oil media.

Nickel alloys, including 825, are generally stronger than most of the simple austenitic stainless steels and the resulting reductions in wall thickness and weight go some way to mitigate the significant cost increase arising from the high nickel content.

## Applications

Alloy 825 is used extensively by the chemical industry in the form of tanks, process vessels, pipework systems, heat exchangers, agitators, rotors and cast valves and pumps, particularly in the manufacture and processing of sulphuric and phosphoric acids. For thick-walled vessels, where the cost of a solid structure might be prohibitive, carbon steel with a cladding of 825 is often used. The resistance to SCC in oil contaminated with chlorides and hydrogen sulphide is increasingly being exploited by the oil and gas industries where pipework and flowlines for critical applications are made from seamless pipe and tube which is internally clad with alloy 825. These pipes are often produced by the hot extrusion of hollow forgings, which are overlaid on the internal surface with 825 weld metal.

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