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The alloy tree

The alloy tree
A guide to low-alloy steels, stainless steels and nickel-base alloys

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CRC Press
Boca Raton Boston New York Washington, DC

WOODHEAD PUBLISHING LIMITED
Cambridge England

Published by Woodhead Publishing Limited, Abington Hall, Abington
Cambridge CB1 6AH, England
www.woodhead-publishing.com

Published in North America by CRC Press LLC, 2000 Corporate Blvd, NW
Boca Raton FL 33431, USA

First published 2004, Woodhead Publishing Limited and CRC Press LLC

British Library Cataloguing in Publication Data
A catalog record for this book is available from the British Library.

Library of Congress Cataloguing in Publication Data
A catalog record for this book is available from the Library of Congress.

Woodhead Publishing ISBN 1 85573 766 3
CRC Press ISBN 0-8493-2575-7
CRC Press order number: WP2575

Typeset by SNP Best-set Typesetter Ltd., Hong Kong
Printed by TJ International, Padstow, Cornwall, England

Contents

Preface

In 1984, a small group in the technical department at Metrode Products Ltd produced a design for a wall chart that illustrated the evolutionary nature of the various alloyed welding consumables which formed the basis of Metrode's product range. The chart was always referred to as 'The Alloy Tree' because the main trunks, side branches and smaller branches that showed the development of various alloy groups resembled a tree. Unfortunately, the wall chart was never published but the idea of a route map that would show the relationship between various alloy types remained. Inevitably, because Metrode's product range was dominated by stainless steels and nickel-base alloys, this particular emphasis has been retained.

This small book is the direct result of those early developments and the original name has been retained in the title *The alloy tree: A guide to low-alloy steels, stainless steels and nickel-base alloys*. It is intended to be a broad introduction to many of the alloys used in petrochemical, power generation and oil and gas engineering. It is not designed to be a formal textbook, but is more of a general guide to the more commonly used alloys and will be of value to the engineer with an interest in the alloy materials available, as well as the emerging metallurgist who has an interest in the field of alloy developments and their areas of application.

Those who are already familiar with the major reference books, some of which are listed in the bibliography, will realise that this book does no more than scratch the surface. Nevertheless, in describing about 100 alloys, it covers a wide range of applications. Inevitably, boundaries have to be defined and this book deals with iron-base and nickel-base systems, and the interaction between the two.

It does not deal with light alloys based on aluminium, magnesium or titanium. At the two extremes of the alloy system, it does not cover simple carbon or very low-alloy steels in any great detail, nor does it make more than passing reference to the highly specialised area of nickel-base superalloys used in the aerospace industries. Those with a particular interest in these excluded groups will have to look elsewhere.

The information given has been obtained from a wide variety of sources, some of the more important of which are given in the bibliography. However, responsibility for the contents lies solely with the author and he accepts full responsibility for any errors and omissions.

J. C. M. Farrar
Denby Dale

Acknowledgements

As mentioned in the Preface, this book is based on a wall chart, designed by the author but never published. It was intended to show the evolution of and relationship between the more important alloy systems in the Metrode range of alloyed welding consumables. This book is also based on the *Metrode Technical Handbook*, which has been a cornerstone of Metrode's technical support package for almost 40 years, and for which the author, as Technical Director, was responsible from 1981 to 2000. This book would not have been possible without the considerable help, support and encouragement of colleagues Adam Marshall, Chief Metallurgist, and Graham Holloway, Technical Support Engineer, who have helped both with the technical content and the proofing of this book.

However, final responsibility for the contents and for any errors or omissions rests solely with the author.

How to use this guide

The alloy tree

The alloy tree diagram on page xiii provides an overview of the most important iron-base and nickel-base alloy groups and how they are linked. It starts with plain carbon mild steel at the bottom and illustrates how increasing alloy content eventually leads to pure nickel at the top. There are two distinct routes: one up the left hand side, which is based on low- or very low-carbon alloys designed primarily for corrosion resistance in aqueous environments, and one up the right hand side which is based on controlled carbon or high-carbon alloys designed primarily for resistance to high temperatures in a range of atmospheres. There are other branches, which deal with low-alloy creep-resisting and cryogenic steels.

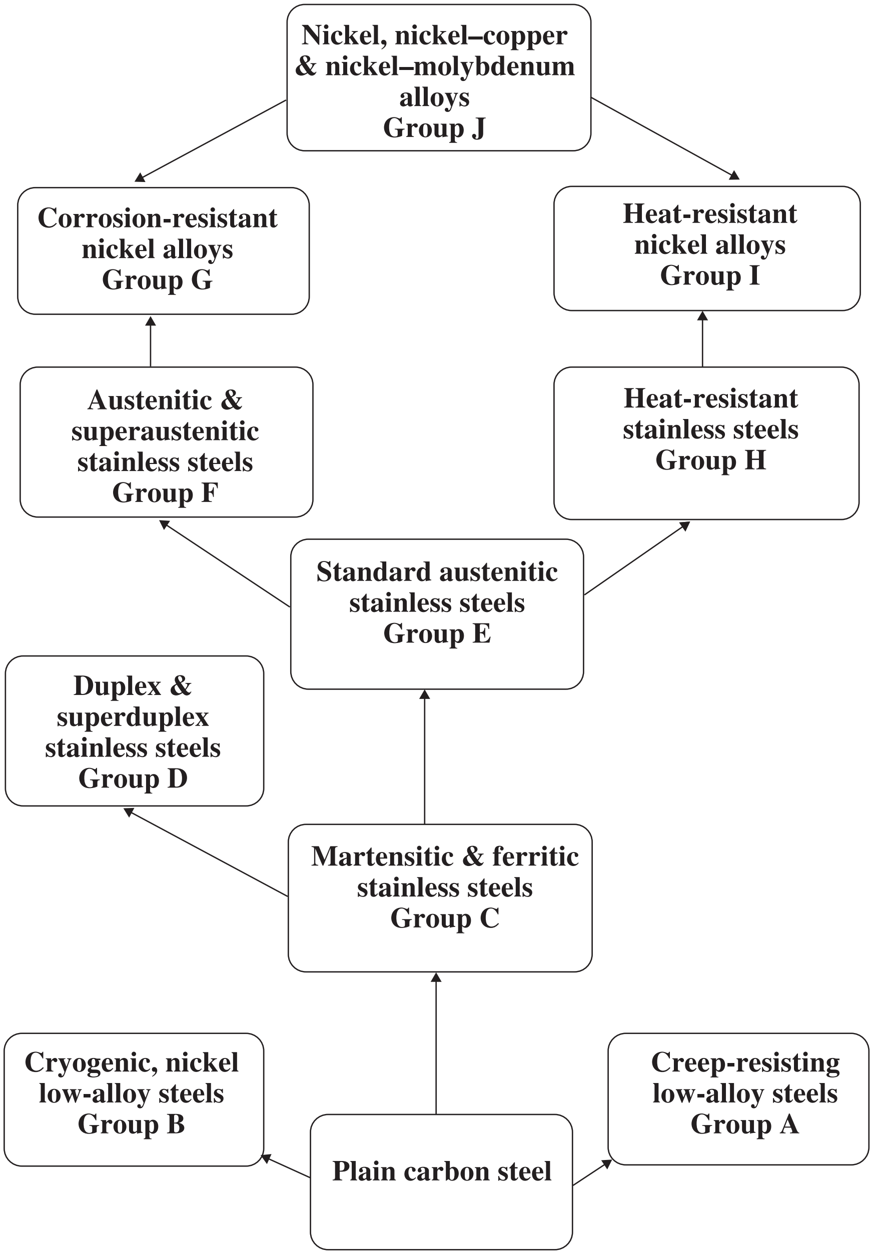
Alloy groups

There are ten alloy groups designated as Groups A to J. The route map within each group shows the detailed relationships between closely related alloys. The route maps also show, in general terms, the changes in alloy content between one alloy and the next. Each alloy, or group of very closely related alloys, carries a reference code, which is the group reference letter, combined with a unique number, and this is the link to each individual data sheet (A–0, A–1, A–2, etc). A very few alloys, which tend to be generic groups in their own right, do not have reference numbers. This means that there is no data sheet but a brief explanation is given in the introduction to each group.

Data sheets

The data sheets are not intended to cover all the detailed information about the properties of a specific alloy. This information is readily available from standard reference books and manufacturer's literature. They do provide a typical composition and some of the more commonly used specifications and proprietary grades, where applicable. Also included is a description of the alloy, some background and history to the alloy development, and key properties relevant to its application. There is also a section on the more important applications and cross-references to other related alloys or applications. The data sheets are deliberately presented in a narrative style, in the hope that the reader will find this less intimidating than a formal data sheet with a mass of numerical data.

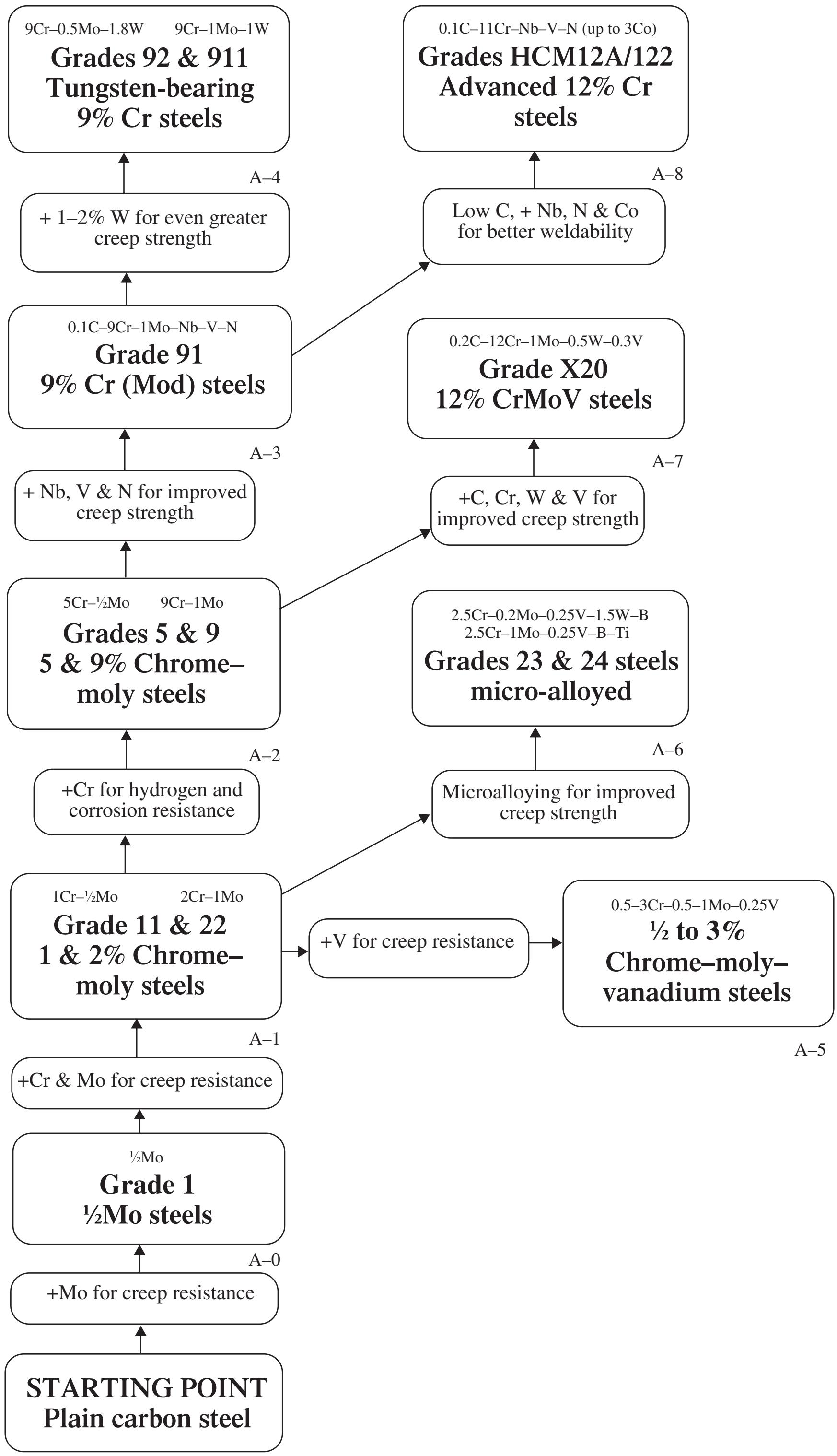
It should be noted that in some of the data sheets the header gives a slightly different composition from that shown in the body of the data sheet. The header shows that which is most widely recognised and is in common usage, whereas the compositions given in the sheet are typical mid-range specification values.



The alloy tree, showing the relationships between the major alloy groups.

Group A

Creep-resisting low-alloy steels



Group A: Creep-resisting low-alloy steels.

Introduction

The starting point for Group A is plain carbon steel with a carbon content of about 0.2% and essential deoxidants such as manganese and silicon. This composition gives a pearlitic structure of modest strength designed primarily for use at ambient temperatures. This group demonstrates the effect of increasing alloy content to improve high-temperature creep performance. It illustrates the evolution from a very simple steel with 0.5% molybdenum, designed for service up to about 450 °C, through to the latest 9 and 12% chromium–molybdenum alloys with complex microalloying, designed for very long-term, high-pressure service at temperatures above 600 °C.

Microstructures change from tempered bainite at the lowest alloy content, through to very strong, tough, tempered martensite with complex carbides and carbonitrides. The most highly alloyed grades, with 12% chromium, are at the threshold of stainlessness, but their application, rather than their composition, means that they are correctly included in this group.

There are a number of side branches, describing steels which do not fall naturally on the main alloy branch, but which are also low-alloy high-temperature steels.

A–O

0.2% carbon, 1% manganese, 0.5% molybdenum fine-grained elevated temperature steel

Also known generically as P1 steels

Description

This steel is a very simple and economic development of plain carbon manganese steels where the addition of only 0.5% molybdenum has a significant effect on high-temperature properties. A typical composition is:

	C	Mn	Mo	Si	S	P	Al
Weight %	0.15	1	0.5	0.3	<0.02	<0.02	0.05

This steel is normally supplied in accordance within one of many national and international standards, a few examples of which are given below:

UNS	ASTM	EN
K12822	Gr. P1	1.5415
K11522		
K12821		
J12522		

These steels are usually supplied in the normalised and tempered (N + T) condition to ensure a fine-grained microstructure with some matrix strengthening and some carbides.

Background

Carbon manganese steels represent the most cost-effective method of alloying, to achieve reasonable strength and toughness combined with good weldability but the addition of only about 0.5% molybdenum gives some improvements in higher-temperature performance and represents the first stage in the evolution of more highly alloyed chrome–molybdenum and chrome–molybdenum–vanadium creep-resisting steels.

Performance

The addition of about 0.5% molybdenum provides a degree of matrix strengthening and a modest increase in strength over the plain carbon–manganese steels. However, the real improvement comes in achieving and retaining tensile strength and providing reasonably good creep strength at temperatures up to about 450 °C. This is still well below that required for modern steam-generating plant but represents a useful improvement over carbon–manganese steels at a very modest cost premium. The molybdenum content also enhances resistance to hydrogen attack.

Applications

These steels are used primarily for the manufacture of process vessels and associated pipework in chemical and oil refinery process plant. They are used for plant operating at modest temperatures often with hydrogen present and offer good creep resistance and ductility at temperatures not exceeding 400–450 °C. For more demanding conditions, higher-alloyed steels would be used.

A–1

$1\frac{1}{4}$% chromium–$\frac{1}{2}$% molybdenum and $2\frac{1}{4}$% chromium–1% molybdenum creep-resisting steels

Also known generically as Grades P11 or P12 and P21 or P22

Description

These steels are plain chromium–molybdenum creep-resisting steels with no additional strong carbide formers. Typical compositions are:

		C	Mn	Si	S	P	Cr	Mo
Weight %	**P11**	0.15	0.5	0.3	<0.02	<0.02	1.25	0.5
	P22	0.07	0.6	0.3	<0.02	<0.02	2.25	1

The steels are normally supplied in accordance within one of many national and international standards, a few examples of which are given below:

	UNS	ASTM	EN
P11	K11597 J12072	Gr. 11 & 12	1.7355
P22	K21590 J21890	Gr. 21 & 22	1.7383

These steels are typically supplied in the normalised and tempered condition and, if subjected to fabrication and welding are usually retempered at about 690 °C. The resultant microstructure is tempered medium carbon bainite with no retained ferrite.

Background

These plain chrome–moly creep-resisting steels are the simplest of the true creep-resisting steels in this group. They rely on matrix strengthening from the chromium and molybdenum and on the same elements to provide carbides for grain boundary and dislocation pinning. These steels were developed in the early part of the 20th century and were the ‘workhorse’ steels used in modern fossil-fuelled power generation plant for many decades until the development and introduction of P91 steels during the late 1970s (A–3).

Performance

These steels are designed for very long-term service in the creep range at temperatures up to about 560 °C and some components and pipework have been in service for more than 250 000 hours (>30 years). However, their creep strength is quite modest when compared with modern advanced steels and this has resulted in the use of very thick-walled components in order to give the necessary performance with high temperatures and pressures. For example, power station main steam pipes often have a wall thickness in excess of 100 mm with obvious implications in terms of fabrication, repair, handling and support costs.

Applications

The main areas of application are steam-generating plant including piping, turbine casings, steam chests, valve bodies and boiler superheaters.

These steels are also widely used in oil refineries and provide good corrosion resistance against sulphur-bearing crude oils at 250–450 °C. They are also used in the chemical and petrochemical industries because of their resistance to hydrogen attack and blistering at temperatures up to about 450 °C. Typical applications are hydrocrackers, coal liquefaction plant and ammonia pressure vessels.

These steels and welded joints can suffer from temper-embrittlement after long periods of high-temperature service, which results in embrittlement and a risk of low-temperature brittle fracture in some process plant. Special grades of steel and weld metals, with low residuals such as phosphorus and arsenic, are used to reduce the risk of serious failures.

A–2

5% chromium–½% molybdenum and 9% chromium–1% molybdenum creep-resisting steels

Also known generically as Grades P5 and P9

Description

These steels are plain chromium–molybdenum creep-resisting steels with no additional strong carbide formers but with significantly more chromium than P11 and P22. Typical compositions are:

		C	Mn	Si	S	P	Cr	Mo
Weight %	**P5**	0.1	0.5	0.5	<0.02	<0.02	5	0.5
	P9	0.1	0.5	0.5	<0.02	<0.02	9	1

The steels are normally supplied in accordance within one of many national and international standards, a few examples of which are given below:

	UNS	ASTM	EN
P5	K41545 J42045	Gr. 5	1.7373
P9	K50400 J82090	Gr. 9	1.7388

These steels are usually supplied in the normalised and tempered condition and, if subjected to fabrication and welding are usually retempered at about 730 °C and 760 °C respectively. The resultant microstructure is tempered medium carbon bainite and martensite–bainite with no retained ferrite.

Background

These steels rely on matrix strengthening from the chromium and molybdenum and on the same elements to provide carbides for grain boundary and dislocation pinning. In this respect they do not offer major benefits over P22 types. However, the increased chromium content provides additional corrosion resistance and protection against high-temperature hydrogen attack and blistering. The steels were developed in the early part of the 20th century and are most widely used in oil refineries and similar plants. The 9%Cr steel formed the basis for the more advanced creep-resisting steel P91 (A–3).

Performance

These steels are designed for long-term service in the creep range at temperatures up to about 600 °C in superheated steam, hot hydrogen gas and high-sulphur crude oils.

Applications

The main areas of application are in oil refineries. Most modern refineries have heat exchangers, pipework and vessels made from Grade 5 steel where resistance to high-sulphur crude oils and hot hydrogen is required. A more recent and common application is in the fabrication of desulphurisation plants used for the production of clean low-sulphur petrol and diesel fuels.

Grade 9 steel is not so widely employed, but it has been used for power plant boiler superheaters as an intermediate grade between the lower alloyed P22 and higher alloyed stainless grades. A limited number of oil refineries, particularly those operating at higher temperatures and producing high-grade metallurgical carbon as a by-product, use Grade 9 steel to provide improved corrosion and hot hydrogen resistance at somewhat higher temperatures.

A–3

Modified 9% chromium, 1% molybdenum creep-resisting steel

Also known generically as Grade P91

Description

P91 is essentially a 0.1% carbon, 9% chromium, 1% molybdenum steel, modified with controlled additions of vanadium, niobium and nitrogen to give long-term, high-temperature creep strength. A typical composition is:

	C	Mn	Si	S	P	Cr	Ni	Mo	Nb	V	N
Weight %	0.1	0.5	0.3	<0.01	<0.02	9	0.1	1	0.08	0.2	0.05

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

UNS	ASTM	EN
K90901 J84090	Gr. 91	1.4903

This steel is supplied in the normalised and tempered condition and, if subjected to fabrication and welding is usually retempered at about 760 °C. The resultant microstructure is tempered medium carbon martensite with little or no retained ferrite.

Background

'Super 9 chrome' alloys were initially evaluated for power boiler use in the late 1950s; however, the present generation of P91 steels arose from a development programme in the USA. In 1974 the Oak Ridge National Laboratory (ORNL) in conjunction with Combustion Engineering initiated a project to develop a 9%Cr–1%Mo alloy steel that combined the advantages of the existing 9%Cr and 12%Cr steels with improved weldability.

Performance

The advantages of P91 steels over established steels such as P22 (2%Cr–1%Mo) and X20 (12%CrMoV) is clearly illustrated by comparing the

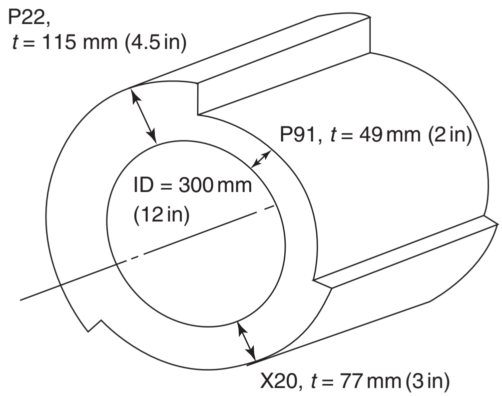


Figure 1 Pipe thicknesses for P91 steel compared with those of P22 and X20 steels, for the same operating conditions.

relative steam pipe wall thicknesses required for a set of typical operating conditions and equivalent service life (temperature 600 °C, pressure 30 MPa, design life 100 000 hours) (Fig. 1).

Applications

The first set of 9%Cr–1%Mo (modified) tubes were installed in superheater sections in May 1980, replacing type 321 stainless steel tubing. By 1983 the steel was recognised for tubing by the American Society for Testing and Materials (ASTM) and for piping by the ASTM and the American Society of Mechanical Engineers (ASME) in 1984.

By the mid-1980s, UK interest in the material was developing and the former Central Electricity Generating Board (CEGB) established a programme that led to the installation of replacement steam headers in P91 at a major coal-fired power station in 1989.

In the 1990s, P91 became the material of choice for the repair and upgrading of existing power stations and for the construction of new units throughout the world. The main areas of application in coal-fired power stations are headers, main steam pipes and turbine casings. It is also used in the many steam lines that are an integral part of modern gas-fired combined cycle power plants. It is in all such items that the major benefits arising from reduced wall thicknesses, reduced weights and consequent cost savings can be realised. Higher operating temperatures and pressures can also lead to improvements in thermal efficiency and reduced carbon dioxide emissions. This is a major driver behind the use of P91 and other, more advanced, creep-resisting steels.

A–4

Modified 9% chromium, 1% molybdenum creep-resisting steel with tungsten

Also known generically as Grade 92/NF616 and E911

Description

These are essentially 0.1% carbon, 9% chromium, molybdenum steels, modified with controlled additions of tungsten, vanadium, niobium and nitrogen to give exceptional long-term, high-temperature creep strength. Typical compositions in weight % are:

	C	Mn	Si	S	P	Cr	Ni	Mo	W	Nb	V	N	B
P92/NF616	0.1	0.5	0.3	<0.01	<0.01	9	0.1	0.5	1.7	0.06	0.2	0.05	0.003
E911	0.1	0.8	0.3	<0.01	<0.01	9	0.1	1	1	0.05	0.2	0.05	-

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

	UNS	ASTM	EN
P92/NF616	K93640	Gr. 92	
E911			X11CrMoWVNb 9 1 1

These steels are supplied in the normalised and tempered condition and, if subjected to fabrication and welding are usually retempered at about 760 °C. The resultant microstructure is tempered martensite with little or no retained ferrite.

Background

These steels are developments of P91 with additions of tungsten to provide very stable carbides and further improve creep strength. P92 was originally developed in Japan in the 1990s as NF616 and was incorporated into the ASTM and ASME code as Grade 92. In this steel the molybdenum content is reduced to 0.5% with an addition of about 1.7% tungsten.

E911 is a result of European developments, which took place over the same period; the result was a slightly different variant with molybdenum held at 1% and a straight addition of 1% tungsten. At the present time this steel is incorporated in the Euro Norm (EN) standards, but is not yet recognised by the ASME code.

Performance

The steels are designed to operate at temperatures up to at least 600 °C and have creep rupture strengths that, it is claimed, are up to 30% greater than P91. These are relatively new steels and data, particularly on welded joints, are still being generated. Assuming that the full potential of the steels can be exploited, it should result in even greater reductions in wall thickness of high-pressure components with consequent weight, fabrication and cost savings.

Applications

The first commercial use of these steels took place in Europe only around the year 2000 and the range of applications is still being developed and explored. The main area of use is in the construction of the most modern high-temperature, high-efficiency fossil-fuelled power stations. Probable components are headers, main steam piping, boiler tubes, turbine casings, steam chests and valves. There may also be future applications in oil refining, petrochemical, coal liquefaction and gasification plants where significant reductions in wall thickness of high-temperature, high-pressure vessels may be possible.

A–5

½–3% chromium, ½–1% molybdenum, ¼% vanadium creep-resisting steels

Also known generically as CrMoV types

Description

These steels are chromium–molybdenum creep-resisting steels with a range of chromium and molybdenum contents plus the addition of about 0.25% vanadium as a strong stable carbide former. Some grades have titanium and boron additions or niobium and calcium. Typical compositions are:

	C	Mn	Si	S	P	Cr	Mo	V
Weight %	0.1	1	0.3	<0.02	<0.02	0.5–3.5	0.5–1	0.25

A number of these steels are vanadium-containing variants of well-established chrome–moly creep-resisting steels. They have not yet been allocated Unified Numbering System (UNS) and EN numbers but are used under ASME code cases as follows:

- 2.25Cr1Mo0.25V – code case 2098-1
- 3Cr1Mo0.25V Ti B – code case 1961
- 3Cr1Mo0.25V Nb Ca – code case 2151 (ASTM Gr. F3V)

The steels are usually supplied in the normalised and tempered condition and, if subjected to fabrication and welding are usually retempered at about 700 °C. The resultant microstructure is tempered medium carbon bainite with vanadium carbides and no retained ferrite.

Background

Creep-resisting steels containing vanadium have been used throughout the second half of the 20th century as an economic alternative to the more highly alloyed types. Fossil-fuelled power stations have taken advantage of the good long-term creep life of ½%Cr–½%Mo–¼%V and 1¼%Cr–1%Mo–¼%V alloys, particularly in main steam lines, valve chests and turbine casings.

More recently, interest has focused on the higher alloy types, particularly those with 3% chromium, 1% molybdenum and ¼% vanadium in order to give high-temperature creep properties suitable for use in high-hydrogen atmospheres. Development of the latest grades started in the mid-1980s and still continues.

Performance

These steels are designed for very long-term service in the creep range at temperatures up to about 580 °C either with high-pressure steam or high-pressure hydrogen.

The lower-alloy grades tend to be used under steam conditions and show a reasonable degree of corrosion/erosion resistance in superheated steam. However, there is a marked improvement in high-temperature rupture strength when the chromium content exceeds $2\frac{1}{4}$% and the 3% chromium grades are usually selected for this type of service.

Applications

The main areas of application for the lower-alloyed types are steam-generating plant including piping, turbine castings, steam chests and valve bodies. However, many of these applications have largely been superseded by more modern alloys such as P91 (A–3).

The main application for the higher chromium types is in the manufacture of highly safety-critical hydrocracker and hydrotreater vessels used in oil refineries. Hydrocrackers are used to crack heavy oils with hydrogen at high temperatures in the range 450–600 °C and pressures up to 100 bars, in order to produce light fuels. To withstand such operating conditions, vessels can have a wall thickness up to 250 mm and can weigh up to 1000 tonnes!

Similar conditions are encountered in hydrotreaters, which are used to remove sulphur in the production of clean, low-sulphur petrol and diesel fuels. High temperatures and pressures are again required in order to minimise coke formation.

A–6

$2\frac{1}{4}$%–$2\frac{1}{2}$% chromium plus alloying creep-resisting steels

Also known generically as Grades T23 and T24

Description

These steels are low chromium (~2%) steels with controlled additions of strong carbide formers and boron to give much improved high temperature creep strength when compared with Grade 22, and at modest additional alloying cost. Typical compositions are:

		C	Mn	Si	Cr	Mo	W	Nb	V	B	Ti
Weight %	**T23**	0.06	0.5	0.3	2.2	0.15	1.6	0.05	0.25	0.002	–
	T24	0.07	0.5	0.3	2.25	1	–	–	0.25	0.004	0.07

As relatively new steels, they have not yet been allocated UNS and EN numbers. However they do have ASTM grades.

	ASTM
T23	A213 Gr. T23 (code case 2199)
T24	A214 Gr. T24

They are usually supplied in the normalised and tempered condition and, if subjected to fabrication and welding are usually retempered at about 730 °C, as required by the ASME code case for T23. However, these steels are often used for relatively thin-walled boiler tubes and are usually put into service without post-weld heat treatment (PWHT). The microstructure is tempered medium carbon bainite with no retained ferrite.

Background

T23 and T24 are modern (late 1990s) developments of the well-established $2\frac{1}{4}$%Cr–1%Mo (T22) steel and are closely related to the CrMoV steels described in A–5.

In the case of T23, the molybdenum is virtually eliminated and replaced by significant amounts of the strong carbide formers, namely tungsten, vanadium and niobium. There is also a very small controlled addition of boron.

With T24, the molybdenum is retained at 1% with a modest addition of vanadium and controlled small additions of titanium and boron, which have a synergistic effect in stabilising the microstructure. Carbon is also maintained at the relatively low level of about 0.07% to improve weldability and thin-walled tubes can be welded without preheat.

Performance

These steels are designed for very long-term service in the creep range at temperatures up to about 600 °C and it is claimed that rupture strength is twice that of Grade 22 (A–1) and comparable with that of the modified 9%Cr–1%Mo modified type Grade 91 (A–3). While most data have been generated for relatively thin-walled boiler tubes, work is now in hand to expand the range of applications and in particular to explore the potential for thicker-walled welded pipework.

Applications

The main area of application at the present time is in the fabrication of boiler waterwalls in ultra-supercritical (USC) boilers in fossil-fuelled power stations. These are designed to operate at very high steam temperatures, in excess of 650 °C, with consequent significant improvements in overall thermal efficiency and reductions in emissions and pollutants. These steels have only recently been developed and a wider range of applications is still being validated.

A–7

12% chromium, molybdenum, vanadium creep-resisting steel

Also known generically as Grade X20

Description

X20 is essentially a 0.2% carbon, 12% chromium, 1% molybdenum steel, with significant controlled additions of vanadium to give long-term, high-temperature creep strength. A variant of this grade also contains 0.5% tungsten for further creep strength. Its typical composition is:

	C	Mn	Si	S	P	Cr	Ni	Mo	V	(W)
Weight %	0.2	0.5	0.3	<0.02	<0.02	12	0.5	1	0.3	(0.5)

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

UNS	AISI	EN
–	Type 422	X20CrMoV 12 1 (1.4922) with tungsten (1.4935)

X20 is supplied in the normalised and tempered condition and, if subjected to fabrication and welding is usually retempered at about 750 °C. The resultant microstructure is tempered moderately high carbon martensite with little or no retained ferrite.

Background

This steel is designed for critical heat- and creep-resisting service at temperatures up to at least 550 °C. It is widely used in the worldwide power generation industry for steam turbine blades. In some countries, particularly in Central Europe and Germany, it has been exploited, throughout the second half of the 20th century, for other components and steam pipes. The steel has to be welded with care and with special procedures to avoid the risk of hydrogen cracking and this treatment adds to the cost and complexity of fabrication. More advanced creep-resisting steels with better properties and improved weldability, such as P91 (A–3), have largely superseded this steel for fabricated components.

There are a large number 12% chromium steels both proprietary and referenced in specifications such as those of the American Iron and Steel Institute (AISI). One of the more well known is Jethete M152, which is similar to X20 but has reduced carbon, increased nickel, increased molybdenum and controlled nitrogen additions of about 0.3%.

Performance

Steel X20 is roughly mid-way in creep performance between P22 and P91. However the chromium content of 12% makes the steel virtually 'stainless' in terms of corrosion resistance and this is beneficial in steam corrosion/erosion and some fireside environments. In this respect it is superior to P22 (A–1) and somewhat better than P91 (A–3).

Applications

The main application area for these steels is in the power generation industry. They are also used in some specialised petrochemical components where the combination of high creep strength and corrosion resistance can be utilised. They are used as shafts and impellors where the corrosive environment is not too severe.

However, the main area of application is in turbine and diaphragm blades. They are more suitable for the high and intermediate pressure stages of steam turbines where there is less risk of wet steam erosion. Higher chromium grades with levels up to about 14% are often used in the low-pressure stages.

A–8

Modified 12% chromium, 0.5% molybdenum, 2% tungsten creep-resisting steel

Also known generically as Grade 122 and HCM12A

Description

P122 is a further development of P91 and P92 with a higher chromium content and balanced additions of strong and stable carbide formers such as molybdenum, tungsten, vanadium and niobium. Like other modern high-temperature low-alloy steels, there is also a controlled nitrogen addition of about 0.06%. A typical composition is:

	C	Mn	Si	S	P	Cr	Ni	Mo	W	Nb	V	N
Weight %	0.1	0.6	0.3	<0.01	<0.02	11.5	0.3	0.5	2	0.06	0.2	0.06

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

UNS	ASTM
K92930	A213 T122 (seamless tubes) A335 P122 (seamless pipes).

This steel is supplied in the normalised and tempered condition and, if subjected to fabrication and welding is usually retempered at about 760 °C. The resultant microstructure is tempered medium carbon martensite with little or no retained ferrite.

Background

This steel can be considered as yet a further evolutionary development of the P91 and P92 types. It was originally developed by Sumitomo Metal Industries within the last decade of the 20th century and was designated as HCM12A. It was recently included in the ASME code with generic designation of grade P122. It has similar creep strength to alloys such as P92 and E911 but the higher chromium content is claimed to give improved oxidation resistance at very high steam temperatures.

On-going steel developments are now looking at non-austenitic steels that are suitable for service up to 650 °C to give further improvements in the thermal efficiency of ultra supercritical (USC) power plants. One of the new steels, designed for boiler applications, contains about 12% chromium, 2.5% tungsten and 2.5% cobalt, the addition of cobalt preventing the retention of delta ferrite in the microstructure. Variants of these steels are also used for turbine rotors.

Performance

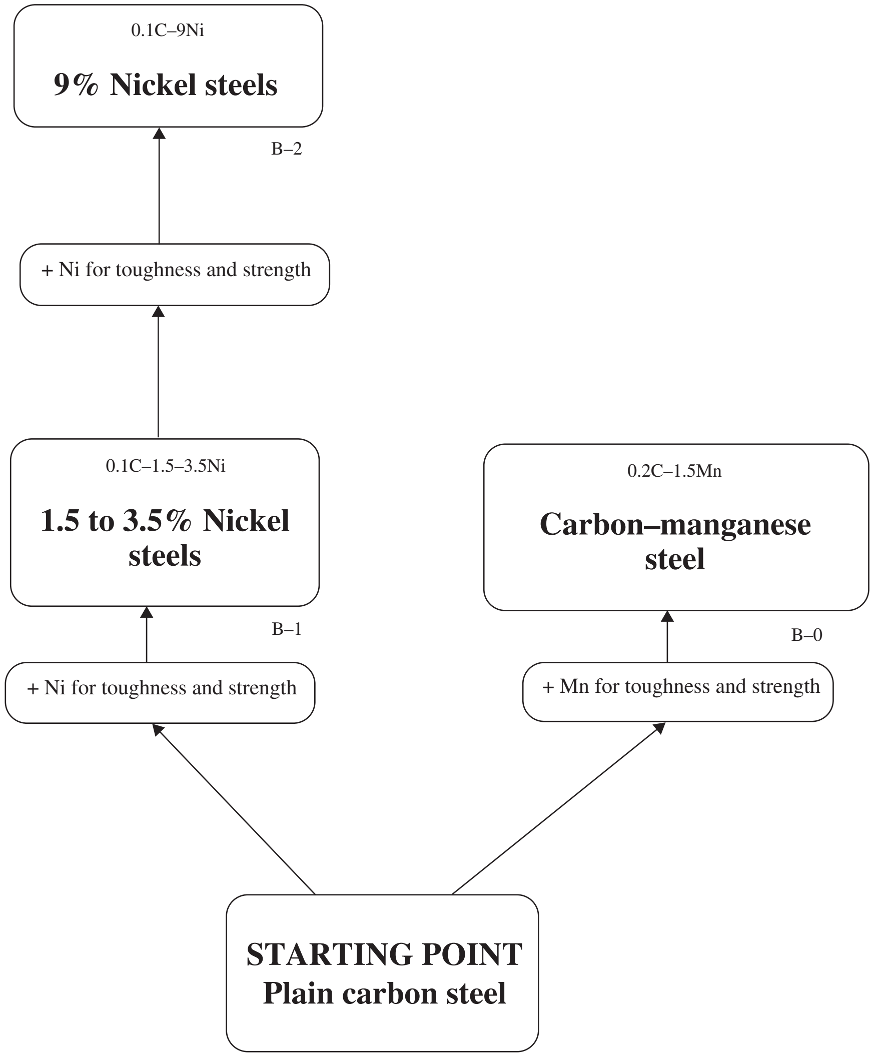
At 600 °C the allowable stresses for P122 are about 30% greater than for P91, permitting further reductions in pressure component wall thickness with consequent reductions in thermal losses, weights and costs. Creep performance is comparable with P92 and E911 at temperatures up to about 650 °C, but the increased chromium content gives improved oxidation and erosion performance at the very high steam temperatures encountered in USC power plants.

Applications

The application of these steels is still fairly limited and to some extent is governed by lack of reliable data covering the long-term creep performance of weld metals and welded joints. Development work is in currently underway and it is anticipated that these advanced steels will soon begin to be used for USC power plant boilers, reheaters, superheaters and turbine rotors. It is also expected that they will be exploited in the most modern combined cycle power plants and in future generations of coal gasification units.

Group B

Cryogenic, nickel low-alloy steels



Group B: Cryogenic, nickel low-alloy steels.

Introduction

As for Group A, the starting point for Group B is plain carbon steel. There are two branches to this simple group. The first of these illustrates the effect of modest increases in manganese, which improves both strength and toughness and enables service down to –50 °C. The alternative branch shows how nickel can increase both strength and toughness. At 2–3% nickel level, steels are produced that are suitable for service down to –100 °C. Increasing the nickel to 9% leads to a low-alloy steel that has high strength and toughness at temperatures as low as –196 °C.

B–0

0.2% carbon, 1.5% manganese fine-grained structural steel

Also known generically as CMn steels

Description

This is a general-purpose steel with a moderate carbon content of 0.2% and about 1.5% manganese to ensure reasonable strength and good weldability. The steel is usually fully deoxidised with silicon and aluminium, and sometimes niobium, and is fine grained for optimum toughness. Its typical composition is:

	C	Mn	Si	S	P	Al
Weight %	0.2	~1.5	0.3	<0.02	<0.02	0.05

The steel is normally supplied in accordance within one of many national and international standards, a small selection of which is given below:

UNS	ASTM	EN
K03008 (wrought)	A333 Gr 1	10025 Gr. S235
K03006	Gr 6	Gr. S275
J03003 (cast)	A352 Gr LCB	Gr. S335
J02505	Gr LCC	

Carbon–manganese steels are usually supplied in the normalised condition to ensure a fine-grained pearlitic microstructure.

Background

Carbon–manganese steels represent the most cost-effective method of alloying to achieve reasonable strength and toughness combined with good weldability. Modern steels are bulk produced in very large oxygen converters and can be refined to give very low levels of sulphur. However, other residuals and tramp elements depend very much on the quantity and quality of scrap being incorporated into the melt. The quality of the final product from different producers can vary somewhat.

Most bulk steels of this type are produced using continuous casting and are therefore fully killed using manganese, silicon and aluminium as deoxidants.

Performance

The properties of these steels depend upon the exact carbon and manganese contents and on the heat treatment and the plate thickness. However, proof strengths up to about 500 MPa can readily be achieved. Provided a correct normalising treatment is carried out, toughness is very good, with excellent properties at sub-zero temperatures and useful properties down to about –50 °C.

Clearly, with no significant alloying content, these steels will corrode rapidly in the open air and more so in marine and industrial environments. They are usually protected by painting, coating or zinc galvanising, depending upon the particular application.

Applications

These are the workhorse grades for the general construction and engineering industries. They are suitable for a wide range of operating conditions where extremes of temperature and corrosive conditions will not be encountered.

They are very widely used in ships, pipelines, bridges, building frames and offshore structures, both fixed and mobile, where good toughness down to well below zero is often an essential design consideration. In addition, they are used in the construction of tanks and pressure vessels for the chemical and petrochemical industries where the temperature range is between about –50 °C and about +250 °C and corrosion conditions are relatively benign.

B–1

1.5%–3.5% nickel cryogenic steels

Also known generically as A333 Gr 9 and Gr 3

Description

These steels are similar to plain carbon–manganese steels but have an addition of 1.5–3.5% nickel to increase strength and, in particular, low-temperature fracture toughness. Grade 9 also contains about 1% copper. In both cases the typical carbon content is reduced to 0.1% since it is not required for alloy strengthening and has a detrimental effect on toughness. These steels are grain refined with aluminium to further improve toughness. Typical compositions are:

		C	Mn	Si	S	P	Ni	Cu	Al
Weight %	**Grade 9**	0.1	0.5	0.3	<0.02	<0.02	2	1	0.05
	Grade 3	0.1	0.5	0.3	<0.02	<0.02	3.5	-	0.05

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

	UNS	ASTM	EN
Grade 9	K31050	A350 Gr. LF5, A352 Gr. LC2	10028
	J22500	A333 Gr. 9	Gr. 1.6228
Grade 3	K13050	A350 Gr. LF3, A352 Gr. LC3	
	K31918	A333 Gr. 3	Gr. 1.5367
	J31550		

These steels are usually supplied in the normalised, normalised and tempered, or quench and tempered (Q + T) condition, to ensure a fine-grained, strong, tough microstructure.

Background

Relatively small amounts of nickel, in the range 2–3%, can result in a significant improvement in fracture toughness, in particular bringing about a reduction in the ductile–brittle transition temperature. In addition, the carbon content can be reduced without seriously compromising tensile strength.

Performance

The properties of these steels depend upon the exact alloying content and on the heat treatment and the plate thickness. However, proof strengths up to about 500 MPa can readily be achieved. Provided a correct normalising treatment is carried out, toughness is very good with excellent properties down to –60 °C for the 2% nickel grades, and –100 °C for the 3.5% nickel grades. It should be noted that it is sometimes difficult to achieve similar properties with matching composition weld metals. For this reason, the 3.5% nickel steels are often welded with nickel-based welding consumables, if good toughness is specified at –100 °C. For lower temperatures, down to –196 °C, 9% nickel steels are used (B–2).

The combination of nickel and copper in Grade 9 also improves corrosion performance and provides some 'weathering' resistance to atmospheric corrosion.

Applications

These alloys are used where operating temperatures below those safe for carbon–manganese steels are likely to be encountered. The main applications are in the oil and gas and petrochemical industries, where they are used for valves, pumps, piping and vessels processing and handling liquefied petroleum gases (LPG), such as propane and butane at temperatures above about –100 °C. They are also exploited in general pressure equipment which may experience a rapid depressurisation and corresponding cooling resulting from adiabatic expansion of the vessel contents.

The enhanced fatigue performance combined with good strength and toughness can be used to advantage in the manufacture of fatigue loaded and rotating engineering components such as shafts and rotors.

B–2

9% nickel cryogenic steels

Also known generically as ‘9% nickel’

Description

These steels are a metallurgical evolution of the lower nickel steels, with the nickel being increased to about 9% to improve fracture toughness and further reduce the safe operating temperature at reasonably modest alloying cost. A typical composition is:

	C	Mn	Si	S	P	Ni
Weight %	0.06	0.6	0.25	<0.01	<0.02	9.5

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

UNS	ASTM	EN
K81340	A333 Gr. 8	1.5662
K71340	A352 Gr. LC9	1.5663
	A553 type I	

They are usually supplied in the quenched and tempered condition to ensure a lath-like martensitic microstructure. Careful temperature control during heat treatment is essential if the optimum microstructure and properties are to be achieved.

Background

Inco (International Nickel Company, now Special Metals) developed 9% nickel steel in 1944 for use at service temperatures down to –196 °C (liquid nitrogen). The alloy was adopted by the ASME code in 1956, but a PWHT was required, which essentially restricted its use to relatively smaller, shop-built fabrications. Following work by U.S. Steel, Inco, and the Chicago Bridge & Iron Company, it was established that the use of PWHT actually had an adverse effect and was not necessary for serviceability and safety. The ASME code was subsequently amended to allow the use of plates up to 50 mm in thickness without PWHT, which opened the way for the steel’s use in the manufacture of very large liquefied natural gas (LNG) storage tanks.

Performance

The 9% nickel steels combine high strength and fracture toughness at temperatures down to at least –196 °C. Typical tensile strengths are greater than 650 Mpa and impact values in excess of 100 J would normally be expected. Fracture mechanics tests such as crack tip opening displacement (CTOD) are usually carried out to validate materials, and values well in excess of 1 mm are achieved.

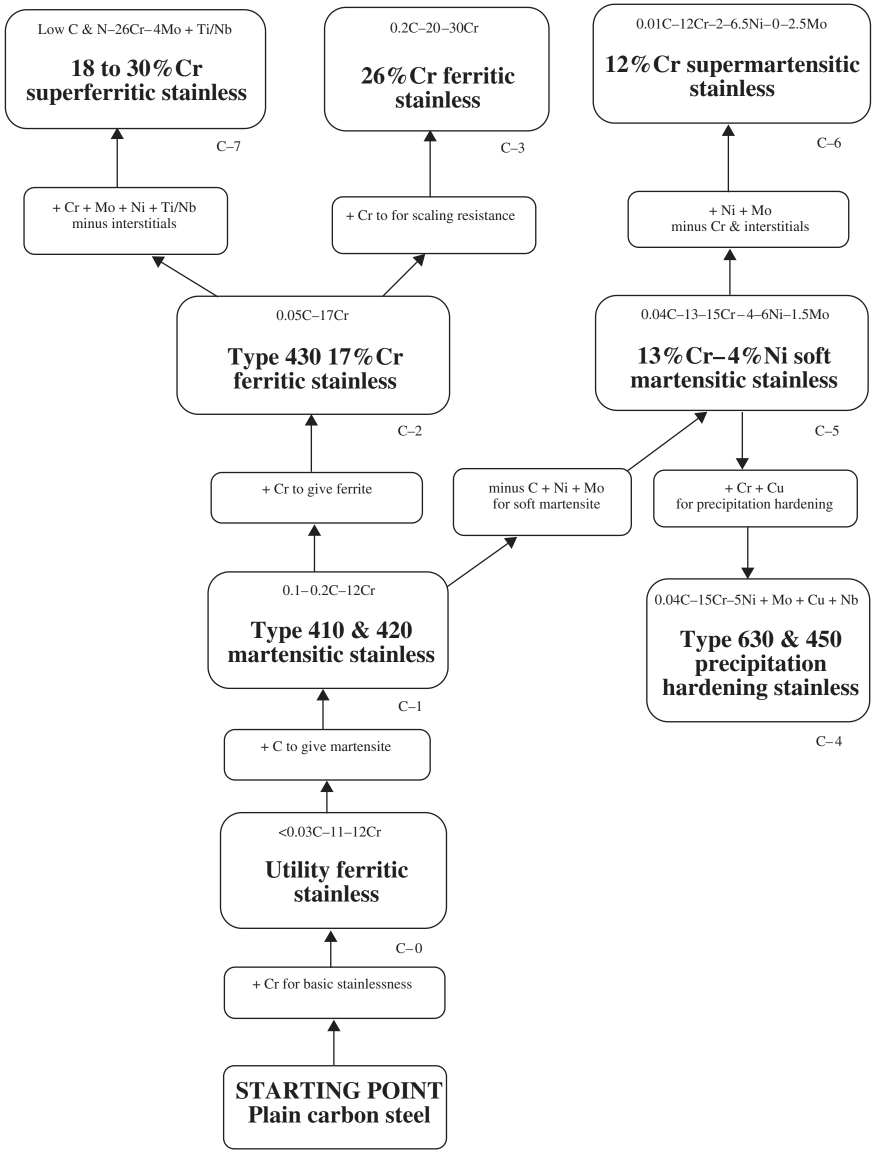
It is almost impossible to obtain the necessary weld metal properties using matching composition 9% nickel welding consumables. For this reason, special high-strength, high-toughness nickel-base welding consumables have been developed that meet the specified requirements and are metallurgically compatible with the base steel.

Applications

The steels are used for handling, transportation and storage of liquefied gases at very low temperatures. By far the most important application is the manufacture of very large, land-based LNG storage tanks and tanks on board LNG carrier ships. These are an essential part of the worldwide storage and distribution of LNG and therefore key to the sustained economic development of many countries that do not have sufficient indigenous energy resources. Needless to say, the bulk storage of highly inflammable liquid gas is safety-critical and every effort is made to ensure the safe construction and operation of these tanks by using only steels from reliable producers, which are subject to extensive testing and validation.

Group C

Martensitic and ferritic stainless steels



Group C: Martensitic and ferritic stainless steels.

Introduction

Group C is a quite complex but very important group, which illustrates the evolution of several different types of stainless steel. The starting point is plain carbon steel and the main route shows how the alloying addition of 12% chromium leads to simple low-carbon ferritic and higher-carbon martensitic stainless steels. Further additions of chromium up to almost 30% lead to the highly oxidation-resistant ferritic stainless steels.

There are two important side branches in this group, both of which illustrate the influence of reducing carbon to very low levels, and introducing quite modest amounts of alloying to give both martensitic and ferritic steels with useful corrosion resistance in aqueous media at moderate cost.

Finally there is a further sub-branch that illustrates the relationship between the soft martensitic types and the precipitation-hardening martensitic types.

The 12% chromium, type 410 alloy is the starting point for both Group D Duplex and superduplex stainless steels and Group E Standard austenitic stainless steels.

C–0

Plain 11–12% chromium steels with very low carbon contents and little additional alloying

Also known generically as types 405, 409 and 410S, or 'Utility ferritics'

Description

These corrosion-resistant 12%Cr steels have been developed with very low carbon contents and close control of the martensite/ferrite balance. Some of the steels are ferritic, leading to the general description 'utility ferritics' but the more modern versions have a dual phase structure, which consists of fine-grained low-carbon martensite and fine-grained ferrite. The microstructures are balanced for ease of forming and fabrication, and to avoid the extremes of properties and welding behaviour usually associated with fully martensitic or ferritic structures. A typical composition is:

	C	Mn	Si	S	P	Cr	Ni
Weight %	0.025	1	0.5	<0.01	<0.02	12	<0.2

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

UNS	ASTM	EN	Proprietary alloys
S40500	Gr. 405	1.4003	Columbus Steel 3CR12
S40900	Gr. 409	1.4512	Krupp Nirosta 4003
S40800	Gr. 410S	1.4000	Avesta Polarit 850

These steels are always supplied directly, controlled-cooled from hot rolled strip or plate.

Background

These steels were developed in the second half of the 20th century as economic bulk production of very low-carbon steels became possible. The early versions were developed by Columbus Steel in South Africa to exploit very large local reserves of chromium; much of the development of these steels has been carried out there.

Performance

These steels combine basic stainlessness with reasonable strength up to about 400 MPa proof stress. Exact properties are dependent upon carbon and minor alloying content, plus microstructure. The best combination of strength and toughness is achieved with thinner materials and most applications use sheet or plate up to about 10 mm in thickness.

Although not primarily designed as high-temperature alloys, these steels offer useful properties up to 450 °C for continuous service and 750 °C for intermittent temperatures/unloaded structures. The 12% chromium content provides good oxidation and scaling resistance in hot and sulphur-bearing flue gases.

These steels are only just stainless and are not designed to compete directly with the 300 series austenitic and duplex stainless steels in more aggressive media. However, they show exceptional wear/abrasion resistance under wet conditions.

Applications

In general terms these steels have properties that bridge the gap between coated, painted or galvanised steels and the more expensive austenitic stainless steels. Although much softer than low-alloy quenched and tempered steels, they are often cost effective for applications requiring wet abrasion resistance.

Typical uses include sugar-refining plant; hoppers, chutes and silos in the metals and minerals handling and processing industries; vehicle/rail car bodies and chassis; fertiliser and refuse-handling plant; high-temperature exhaust ducts and flues.

Concerns over heat-affected zone (HAZ) properties and toughness mean that these steels are not used in pressure-containing structures, but they are often exploited in other safety-critical structures such as road and rail vehicles. Special testing is carried out to ensure fitness for purpose.

C–1

Plain 11–13% chromium martensitic steels with various carbon contents

Also known generically as types 410 and 420

Description

These steels contain 11–13% chromium with minimal additional alloying. The older standard grades such as 410, 420, etc. have carbon contents in the range 0.1 to 0.2%, are air hardening and give a predominantly martensitic microstructure. The steels are invariably heat treated before use and then contain tempered martensite with varying levels of chromium carbide and retained ferrite. The more modern related grades have lower carbon contents and some small alloying additions to improve weldability (C–5). A typical composition is:

	C	Mn	Si	S	P	Cr	Ni
Weight %	0.1–0.2	1	0.5	<0.01	<0.02	12	<0.2

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

UNS	ASTM	EN
S41000	Gr. 410	1.4006
S42000	Gr. 420	1.4021
		1.4028
		1.4031
		1.4034

They are usually supplied in the annealed or normalised and tempered condition to give a tempered martensitic microstructure.

Background

These steels are the modern successors to Brearly's air-hardening cutlery steel, which is generally recognised as the first stainless steel and was developed very early in the 20th century. The steels with about 12%Cr are just stainless and corrosion is prevented by the formation of a stable chromium oxide film. They represent the starting point for the evolution of all the stainless steels, culminating in the latest superduplex, superaustenitic and superferritic alloys.

Performance

Type 410 and 420 steels combine basic stainlessness with very high strength, proof stresses in excess of 1000 MPa and limited toughness. They retain tensile properties at elevated temperatures and at 600 °C maintain about 45% of their room temperature strength.

Plain 12% chromium steels have corrosion resistance in a limited range of media and are not intended to compete with more the highly alloyed austenitic and duplex alloys. However, they have very good resistance against hot oils and wet carbon dioxide. They also have useful abrasion and cavitation resistance because of their high hardness.

Applications

Most applications are designed to exploit one or more of the following features:

- basic stainlessness;
- modest cost;
- high strength at both ambient and elevated temperatures.

Applications include hydro crackers, reactor vessels, distillation plant and associated pipework in oil refineries. The steel industry also makes extensive use of these alloys in furnace parts, linings and run out rolls, particularly in continuous casting plants.

They are also used for cast steam valve bodies, pumps, shafts, turbine parts and burner nozzles where modest corrosion resistance and high-temperature properties are required. Finally they have largely displaced mild steel plus corrosion inhibitors, for oil-well down-hole tubulars where operating conditions are not too extreme.

C–2

Plain 17% chromium ferritic stainless steels

Also known generically as types 430 and 430Ti

Description

These steels are, in principle, ferritic at all temperatures. This is achieved by increasing the level of ferrite formers, in this case chromium, to about 17% and by maintaining low levels of austenite formers such as nickel. Small additions of silicon and titanium in grade 430Ti improve weldability and high temperature performance. Typical compositions are:

		C	Mn	Si	S	P	Cr	Ni	Ti
Weight %	**Type 430**	0.05	1	0.3	<0.01	<0.02	17	<0.5	–
	Type 430Ti	0.04	1	0.6	<0.01	<0.02	17	<0.5	0.4

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

UNS	ASTM	EN
S43000	Gr. 430	1.4016
	Gr. 430Ti	1.4510
		1.4511

These steels are usually supplied in the softened or annealed condition to give a fully ferritic microstructure.

Background

Alloy 430 was a relatively early development following the discovery of stainless steels early in the 20th century. It was found that by increasing the chromium content by about 5%, the microstructure changed from being martensitic to become fully ferritic, and quite different and useful properties could be exploited. However, these alloys are sensitive to embrittlement at temperatures around 500 °C and also during welding.

About 1980, an improved grade with slightly increased silicon and titanium was introduced and this has enhanced weldability in thin sections and long-term scaling resistance. The presence of titanium restricts grain growth and embrittlement in the weld HAZ.

Performance

These steels have good general atmospheric corrosion and high-temperature oxidation resistance (better than type 410, because of the increased chromium content) and will resist water, steam and all the organic acids in moderate concentrations. They also show good resistance to commercial grades of detergents and alkaline solutions. They are not resistant to most mineral acids or to chlorides.

A particular feature of the alloys is their resistance to hot sulphur-bearing gases from coal- and oil-burning furnaces and, in this respect, they are superior to most nickel-bearing alloys. Grade 430Ti has excellent scaling resistance up to about 850 °C and also resists cyclic oxidation.

Applications

Most applications for type 430 exploit its good general corrosion properties, coupled with easy formability and the steel is widely used in domestic appliances, automotive and decorative trims, stainless steel sinks and food preparation surfaces and window fitments. Resistance to sulphur-bearing flue gases is often exploited in furnace parts and ducting. However, prolonged exposure at temperatures around 500 °C (so called '475 embrittlement') does result in a severe loss of ductility and the alloy should not be used for critical load-bearing components in such situations.

Type 430Ti is the preferred high-temperature alloy because of its good weldability. Very large quantities are used in the manufacture of automotive exhaust systems and catalytic converters. It is also used in water heaters and heat exchangers.

C–3

Plain 26% chromium ferritic stainless steel

Also known generically as type 446

Description

This steel is, in principle, ferritic at all temperatures and is non-heat treatable. It is an evolutionary development of type 430 with a further increase in chromium to about 26%. It contains no other significant alloying other than carbon up to a maximum of about 0.2%. A typical composition is:

		C	Mn	Si	S	P	Cr	N
Weight %	Type 446	0.1	0.7	0.5	<0.01	<0.02	26	0.1

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

UNS	AISI	EN
S44600	Gr. 446	1.4762

This steel is always supplied in the fully softened condition to give a fully ferritic microstructure.

Background

Alloy 446 was again a relatively early development following the discovery of stainless steels early in the 20th century. It was found that by more than doubling the chromium content of Grade 410 to about 26%, the microstructure changed from being martensitic to become fully ferritic, and quite different and useful properties could be exploited. However, these alloys are sensitive to embrittlement at temperatures around 500 °C and also to HAZ grain growth during welding.

Performance

These steels have good general atmospheric corrosion and high-temperature oxidation resistance; better than type 430. In terms of aqueous corrosion they offer no real benefits over other stainless alloys of similar cost and the difficulties in welding and fabrication restrict their use to high-temperature applications.

Like alloy 430, a particular feature is their resistance to hot sulphur-bearing gases from coal and oil burning furnaces and, in this respect, they are again superior to most nickel-bearing alloys. They are particularly resistant to oxidation and erosion when in contact with molten glass.

Applications

Most applications for type 446 steels exploit their high-temperature oxidation resistance and resistance to sulphur-bearing atmospheres and to erosion by molten glass. Difficulties in forming and HAZ grain growth and embrittlement during welding mean that fabrications are limited. Most applications use thin sheet or strip for light construction or castings for heavier components. They are used by a wide range of industries for boiler baffles, furnace parts, oil burner components, kiln linings, annealing boxes and industrial muffle furnaces.

They are widely exploited in glass manufacture and particularly in glass moulds, where they have been found to be superior to most other, more expensive, heat-resisting alloys.

C–4

14–17% chromium, 5% nickel, 2–3% copper, precipitation-hardening stainless steels

Also known generically as alloys 630 and 450

Description

These steels are representative of a large range of 'lean' chromium–nickel martensitic stainless steels that contain copper and, as a result, undergo a precipitation-hardening reaction when appropriately heat treated. Some of these alloys also contain molybdenum to improve pitting corrosion resistance and niobium to provide some stabilisation. They are quite closely related, in terms of composition, to the soft martensitics. Two grades, 17/4PH and FV520B, are described. Typical compositions are:

		C	Mn	Si	S	P	Cr	Ni	Mo	Cu	Nb
Weight %	**17/4PH**	0.03	0.6	0.4	<0.01	<0.02	16.5	4	0.2	3.5	0.2
	FV520B	0.05	0.7	0.3	<0.01	<0.02	14	6	1.6	1.7	0.3

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

	UNS	ASTM	EN	Proprietary alloys
17/4PH	S17400	A564 Gr. 630	1.4542	Armco Steel 17/4PH Carpenter Custom 630
FV520B	S45000	A564 Gr. XM-25	1.4532	Firth Vickers FV520B Carpenter Custom 450

These steels are always solution treated followed by an ageing treatment, which will determine the final strength. The microstructure consists of tempered martensite further strengthened by secondary or precipitation-hardening reactions.

Background

These steels were developed mid-way through the 20th century on both sides of the Atlantic. In the USA, the Armco Steel Company introduced 17/4PH, while at about the same time Firth Vickers in Sheffield were working on FV520B. The resulting alloys are similar and both rely on a significant amount of copper to promote precipitation hardening, which in turn leads to the very high strength of these alloys.

Performance

These steels combine exceptionally high strength with a reasonable degree of corrosion resistance. They can be aged to give proof strengths in excess of 1100 MPa, about three times the strength of the 300 series alloys (E–0, E–1, E–3), or they can be supplied overaged with reductions in proof strength to about 600 MPa. The exact heat treatment depends on the application, but it should be noted that at the highest strength levels, ductility and toughness are reduced, and the steels are rather sensitive to stress corrosion cracking (SCC). They also maintain strength up to about 300 °C.

The corrosion resistance of 17/4PH is similar to that of type 304L (E–1), whereas that of FV520B is somewhat better, particularly pitting resistance, because of the additional molybdenum content. Although these alloys are classed as stainless, they were not primarily designed for use in aggressive environments.

Applications

Common applications include aircraft components, such as high-strength undercarriage parts, centrifuge bowls, compressor impellors, food machinery parts, machine tools, propeller shafts, pump impellers, rotors and valve bodies and certain gas turbine components. The industries that typically exploit the unique combination of properties are chemicals, oil and gas, pulp and paper, marine, aerospace and power generation.

C–5

Low-carbon 13% chromium steels with 4.5% nickel and 1.5% molybdenum

Also known generically as types CA6NM and F6NM

Description

These so called 'soft martensitics' are a development of the plain 12% chromium steels in that they have a lower carbon content with additions of 4 to 6% nickel and 0.5 to 1.5% molybdenum. The result of these compositional modifications is to greatly improve toughness and weldability with relatively little reduction in strength. A typical composition is:

	C	Mn	Si	S	P	Cr	Ni	Mo
Weight %	0.04	0.75	0.3	<0.01	<0.02	13	4.5	0.75

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

UNS	ASTM	EN
S41500	F6NM (wrought) CA6NM (cast)	1.4313

Soft martensitic steels are always supplied in the tempered condition and the microstructure consists of a fine lath martensite with little or no residual ferrite. A very fine dispersion of stable austenite is formed during heat treatment and this contributes to the relatively high toughness of these alloys.

Background

These steels were developed in the second half of the 20th century as economic bulk production of very low-carbon steels became possible. Originally they were produced mainly as castings but since about 1970, forgings have become more widely available. The most commonly used grade is that given above but a higher alloyed version with 16% chromium, 5% nickel and 1.5% molybdenum is quite popular in Europe for use in more aggressive environments.

Performance

The soft martensitic stainless steels fall mid-way between the plain 12% chromium steels and the more highly alloyed austenitic stainless steels such as type 316L (E–3). They have much higher strength than the austenitics, with a proof strength of up to 800 MPa. However, their corrosion resistance is more limited and they have pitting resistance equivalent (PRE) values in the range of 15 to 21.

Cast alloys have good toughness down to at least –50 °C and useful values can be obtained at –100 °C, with the correct heat treatment. Forged versions generally have better toughness than castings.

These alloys were not primarily designed for elevated temperature applications. Nevertheless, they retain strength up to about 400 °C, at which point they tend to show the ductility dip common to most 12% chromium steels.

Applications

The alloys have good general corrosion resistance and some resistance to stress corrosion cracking in carbon dioxide and hydrogen sulphide environments. They are also particularly resistant to wet abrasion and cavitation, and are widely used in the following areas:

- Heavy section water turbine components for hydroelectric power generation including runners, impellors, diaphragms, diffusers, impulse wheels and propellers.
- Pumps and valve bodies for the power generation and petrochemical industries, particularly in cooling systems handling brackish water.
- Wellhead equipment for the offshore oil and gas industries where the combination of very high strength and reasonable corrosion resistance can result in significant topside weight savings.

C–6

Extra low-carbon 11–13% chromium steels with various levels of nickel and molybdenum

Also known generically as supermartensitic stainless steels

Description

These so-called 'supermartensitics' are a development of the soft martensitics with very low levels of interstitial elements, particularly carbon and nitrogen. Three grades are recognised, usually described as lean, medium and high alloyed. The lean grade has only about 2% nickel and no molybdenum, whereas the medium grade is rather like a soft martensitic with 4.5% nickel and 1.5% molybdenum, but with extra low carbon. The high-alloy grades contain about 6% nickel, 2–2.5% molybdenum and, sometimes, about 0.5% copper. Typical compositions are:

		C	Mn	Si	S	P	Cr	Ni	Mo	N
Weight %	**'Lean'**	0.01	1.5	0.2	<0.01	<0.02	11	2	-	<0.01
	'Medium'	0.01	1	0.2	<0.01	<0.02	12	4.5	1.5	<0.01
	'High'	0.01	1	0.2	<0.01	<0.02	12	6	2.5	<0.01

The steels are always supplied in the tempered condition and have a microstructure of very low-carbon 'soft' tempered martensite with inherent high strength and toughness. Some finely dispersed austenite will be present but little, if any, ferrite.

As relatively new steels that are still under development, they have not yet been allocated UNS or EN numbers. However, they are offered by a number of steel producers under various proprietary designations. Examples are:

- Sumitomo: Super 13Cr series (three grades).
- Industeel: Fafer X80 (three grades).

Background

These steels were developed in the last quarter of the 20th century as new steel-making technology was developed that enabled steels to be produced with extremely low levels of interstitial elements such as carbon and nitrogen, together with low levels of residual elements. The result of this technology was the development of a range of very high-strength, weldable martensitic steels, with excellent toughness.

Performance

Supermartensitics can be produced with proof strengths up to about 850 MPa and more than meet the requirements of X80 and X100 pipeline specifications. Toughness is dependent on optimum heat treatment, but it is generally considered that the lean grades are suitable for temperatures down to –20 °C, whereas the medium and high-alloy grades are suitable for service down to –40 or –50 °C.

The supermartensitics exhibit good strength retention up to about +250 °C, when compared with duplex stainless steels. They have good corrosion resistance to dissolved carbon dioxide, often under saline conditions, with useful resistance to pitting and SCC in the presence of some hydrogen sulphide. Resistance to SCC increases markedly with grade and alloy content.

Applications

The main uses, particularly in the offshore oil and gas industry, are for line pipes, flowlines, tube bundles and downhole tubulars requiring high strength combined with reasonable corrosion resistance. For these types of application, they occupy an economic niche between carbon and low-alloy steels, which have to be used with corrosion inhibitors, and the more expensive and highly alloyed duplex stainless steels.

Applications for these steels are still being evaluated and some problems relating to hydrogen cracking still have to be resolved. Nevertheless, it is expected that they will be more widely exploited in the future as a greater range of product forms become available.

C–7

Extra low-carbon, 29% chromium, 4% molybdenum superferritic stainless steel

Also known generically as superferritics

Description

These steels are based upon type 446 (C–3) as a starting point with typically 29% chromium and up to about 4% molybdenum. Carbon is controlled to very low levels, typically 0.02% or less and they have titanium and/or niobium to a combined level of about 0.6%. These steels are fully ferritic, but because of the very low carbon content and the titanium additions, grain growth and consequent embrittlement is reduced but not eliminated. A typical composition is:

	C	Mn	Si	S	P	Cr	Mo	Ti + Nb
Weight %	0.02	0.5	0.35	<0.01	<0.02	29	4	0.6

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

UNS	EN	Proprietary alloy
S44735	1.4592	Allegheny Ludlum AL 29-4C®

These steels are always supplied in the fully softened condition.

Background

Somewhat like superduplex, superaustenitic and supermartensitic stainless steels, superferritics represent fairly recent developments to significantly improve the aqueous corrosion resistance of existing standard alloys. In all cases, part of the improvement has depended on changes in alloy steel-making technology to give very low-carbon contents. Alloy AL 29-4C was developed in the early 1980s for welded condenser tubing to be used in sea-water and brackish water by the power generation industry and is considered, because of the absence of nickel, to be cost competitive with higher alloys of similar performance.

Performance

These steels were designed for their corrosion resistance in aqueous media and show excellent resistance to pitting and crevice corrosion by chloride ions. In addition, the ferritic microstructure provides effective immunity to chloride-induced SCC.

The PRE value for these steels is typically about 40, which makes them comparable with many superduplex and superaustenitic alloys.

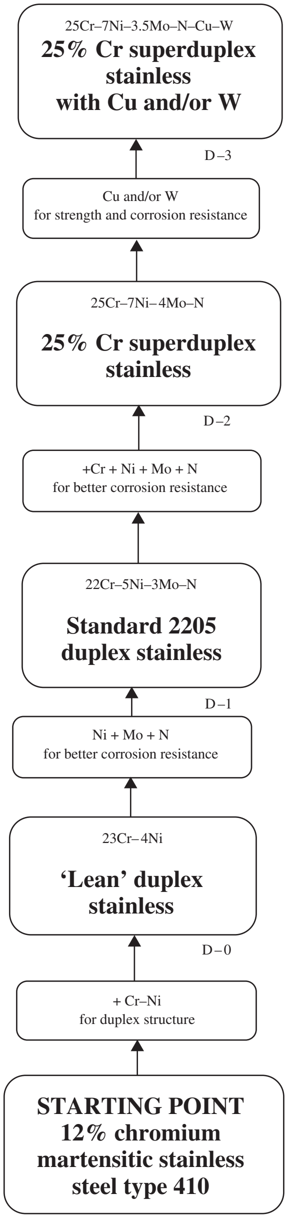
However, unlike the other alloys, they are not readily weldable in thicker sections because HAZ grain growth, serious embrittlement and a consequent reduction in toughness would limit their use for safety-critical, lower-temperature applications.

Applications

For the reasons given above, supply of the superferritics is restricted to thin sheet and strip up to a maximum thickness of about 2 or 3 mm. The most common applications include welded tubing for heat exchangers and condensers, of which many thousands of kilometres have been supplied. The alloys are increasingly being used in gas-fired heating and ventilation systems, particularly in hot ducts and flues. Most modern high-efficiency gas-fired systems experience dew point cooling during normal operation; these condensates are contaminated by minor impurities in the gas and the burner air, which give rise to acid conditions with sulphur and chlorides present. Superferritics have proved to be highly successful in combating these corrosion problems.

Group D

Duplex and superduplex stainless steels



Group D: Duplex and superduplex stainless steels.

Introduction

The starting point for Group D is the plain 12% chromium martensitic stainless steel. The simple addition of chromium and a modest amount of nickel changes the microstructure from martensite to a duplex ferritic-austenitic microstructure and at the same time improves corrosion resistance. The remaining alloys in the group maintain a similar microstructural duplex balance but with progressively increasing alloy content, and corresponding improvements in corrosion resistance. The superduplex types with a PREn > 40 and additional alloying in the form of copper and/or tungsten probably represent the limit of alloy development for this group. Any further alloying would make the material too sensitive to heating and would result in the very rapid development of undesirable intermetallic phases in the weld HAZ and weld metals, resulting in loss of toughness and corrosion resistance. This would effectively limit fabrication using currently available welding processes, and hence the alloys' potential usefulness.

D–0

Lean alloy duplex stainless steels

Also known generically as 2304 duplex

Description

These steels are the so-called 'lean duplex' grades with low carbon, 18–23% chromium, 3–7% nickel, up to 3% molybdenum, up to 1.5% copper and in some cases controlled nitrogen additions. The compositions are all balanced to give a duplex microstructure with about 50% austenite and 50% ferrite. Typical compositions are:

		C	Mn	Si	S	P	Cr	Ni	Mo	Cu	N
Weight %	**3RE60**	0.03	1.5	1.5	<0.01	<0.02	18	4.5	2.5	-	-
	2304	0.03	2.5	0.5	<0.01	<0.02	23	4.5	-	0.3	0.15
	UR50	0.04	2	0.5	<0.01	<0.02	22	7	2.5	1.5	0.1

The steels are normally supplied as proprietary alloys in accordance with one of the following UNS specification numbers:

UNS/ASTM	EN	Proprietary alloys
S31500	1.4362	Sandvik 3RE60
S32304		Sandvik 2304
S32404		Industeel UR50

These steels are always solution treated followed by quenching to give an approximately 50% austenite, 50% ferrite duplex structure without any deleterious phases such as sigma. They have typical pitting resistance equivalents (PREn) ranging from 26 up to about 32.

Background

Lean alloy duplex stainless steels were the predecessors to the 2205 standard duplex alloys. They range in composition from 3RE60, which is essentially a 316L alloy with reduced nickel, to give a duplex microstructure, up to UR50 which has additions of copper and nitrogen and is quite close in alloy content and PREn value to the standard 2205 types (D–1). These steels were designed to give corrosion resistance comparable to standard austenitic alloys such as 316L and 317L (E–3 and F–0) but with improved strength and at reduced cost because of the lower nickel content.

Performance

Duplex stainless steels offer the following:

- High strength – about twice that of standard austenitic stainless steel grades such as 316L.
- Good general corrosion resistance, comparable to 316L and 317L grades in a wide range of environments.
- High resistance to chloride-induced SCC because of their high ferrite content.
- Moderate resistance to pitting attack in chloride environments, e.g. seawater, dependent upon molybdenum content and PREn values.

Applications

These alloys have widespread application in the chemical, offshore oil and gas and pulp and paper industries, but because of their relatively modest corrosion resistance they now have a small market share when compared with the standard 22% chromium, 2205 types (D–1).

Alloy 3RE60 is used for heat exchanger tubing, in combination with carbon steel shells, where there is a need for some stress corrosion resistance.

Alloy 2304 is used by the offshore oil and gas industries particularly for piping systems, mechanical tensioning systems, and umbilical sheathing where its mechanical properties, particularly strength, are more important than corrosion resistance.

Alloy UR50, with a higher PREn value and copper additions, was developed for the chemical industry and for digester preheaters, evaporators, and bleaching and pulp storage tanks for the paper industry. As operating conditions have become more aggressive, superduplex and superaustenitic alloys have largely superseded its use.

D–1

22% chromium, standard duplex stainless steels

Also known generically as 2205 duplex

Description

These steels are the standard duplex grade with low carbon, 22% chromium, 5% nickel, 3% molybdenum and controlled nitrogen additions. They have a reduced nickel content compared with standard austenitic stainless steels to give a duplex microstructure, and molybdenum and nitrogen for corrosion resistance. A typical composition is:

	C	Mn	Si	S	P	Cr	Ni	Mo	N
Weight %	0.03	1	0.3	<0.01	<0.02	22	5	3	0.17

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

ASTM	UNS	EN	Proprietary alloys include
A182 Gr F51 (wrought)	S31803	1.4462	AvestaPolarit 2205
A890 Gr 4A (cast)	S32205		Sandvik SAF2205
	J92205		Sumitomo SM22Cr
	(cast)		Industeel UR45N/UR45N+

These steels are always solution treated followed by quenching to give an approximately 50% austenite, 50% ferrite duplex microstructure without any deleterious phases such as sigma. They have typical PREn of 35 or more.

Background

Duplex stainless steels were first developed in the 1930s for their combination of strength and corrosion resistance. However, it was only during the 1950s and 1960s that they started to be more widely used as castings, and only during the 1970s that they become widely available as wrought material, particularly pipe, tube, plate and forgings. During this latter period the importance of nitrogen as an austenite stabiliser and its role in improving weld HAZ microstructure and properties became more fully appreciated. As production technology for their manufacture has evolved, they have rapidly become a cost-effective alternative to many other grades of stainless steel. By the year 2000 they had become the third most widely used grade of stainless steel in Europe, after types 316L and 304L (E–3 and E–1).

Performance

These steels offer the following:

- High strength – about twice that of standard austenitic stainless steel grades such as 316L.
- Good general corrosion resistance in a wide range of environments.
- High resistance to chloride-induced SCC because of their high ferrite content.
- High resistance to pitting attack in chloride environments, e.g. seawater.

Applications

The offshore oil and gas industry has been a major driver behind the development and use of duplex stainless steels. They have been widely used for process pipework, flow lines, risers, manifolds and firewater systems.

Their benefits are now more widely appreciated, and they are used in land-based chemical and petrochemical plants. Large quantities have been used in the construction of chemical-carrying seagoing vessels and river barges.

In recent years, architectural and general engineering uses have been developed, including the construction of bridges where the combination of high strength and lack of need for maintenance can be exploited economically.

D–2

25% chromium, superduplex stainless steels

Also known generically as 2507 superduplex

Description

These steels are the superduplex grade with low carbon, 25% chromium, 7% nickel, 4% molybdenum and further controlled nitrogen additions when compared with the 2205 types. They still give a duplex microstructure and the higher molybdenum and nitrogen contribute to an improvement in corrosion resistance. A typical composition is:

	C	Mn	Si	S	P	Cr	Ni	Mo	N
Weight %	0.03	1	0.3	<0.01	<0.02	25	7	4	0.25

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

ASTM	UNS	EN	Proprietary alloys include	
A182 Gr F53 (wrought)	S32750	1.4410	Industeel	UR47N
	J93404 (cast)		Sandvik	SAF2507

These steels are always solution treated followed by quenching to give an approximately 50% austenite, 50% ferrite duplex microstructure without any deleterious phases such as sigma. They have a typical PREn of >40.

Background

Some duplex stainless steels with PREn values between 35 and 40 and improved corrosion properties have existed as casting alloys since the 1970s. However, developments in steel manufacturing and processing technology, coupled with demands from the offshore oil and gas industry for further improvements in corrosion resistance for more aggressive environments, led to the development of the wrought superduplex stainless steels. Superduplex stainless steels are usually defined as alloys with a PREn value of at least 40. They have become readily available in the last 20 years but command a much smaller market share than the standard 2205 types. Apart from their higher cost they are, because of their higher chromium and molybdenum contents, more sensitive to sigma formation during welding and heat treatment. Sigma and other deleterious intermetallic phases can form rapidly in the critical temperature range of ~400–800 °C and have an adverse effect on corrosion resistance, ductility and toughness. For these reasons, superduplex alloys tend to be chosen only when the increased performance can justify the additional costs and complexities of fabrication.

Performance

These steels offer the following:

- High strength – more than twice that of standard austenitic grades such as 316L (E–3), and about 10% higher than standard 2205 grades.
- Very good general corrosion resistance in a wide range of environments.
- High resistance to chloride-induced SCC because of their high ferrite content and moderate resistance to hydrogen sulphide-induced SCC.
- High resistance to pitting attack in more aggressive chloride environments, e.g. seawater at higher temperatures.

Applications

The offshore oil and gas industry is the major user of these alloys. Applications are much the same as for the standard 2205 types namely, process pipe work, flow lines, risers, manifolds and seawater systems, etc. They are generally used where corrosion conditions are somewhat more aggressive or where operating temperatures are higher. The use of these alloys in the general chemical and petrochemical industries is still rather limited.

D–3

25% chromium, superduplex stainless steels with copper and/or tungsten

Also known generically as Zeron 100, Sumitomo DP3W, Ferralium SD40, etc.

Description

These are superduplex grades with low carbon, 25% chromium, 7% nickel, 3.5% molybdenum, controlled nitrogen and additions of copper and/or tungsten. They still give a duplex microstructure and the copper and tungsten contribute to an improvement in corrosion resistance in a wider range of environments and also to providing some further increases in strength. Typical compositions are:

		C	Mn	Si	S	P	Cr	Ni	Mo	W	Cu	N
Weight %	**Zeron 100**	0.03	0.7	0.3	<0.01	<0.02	25	7	3.5	0.7	0.7	0.25
	DP3W	0.03	0.6	0.3	<0.01	<0.02	25	7	3	2	-	0.26
	SD40	0.03	1	0.7	<0.01	<0.02	26	6.5	3.3	-	1.6	0.26
	UR52N+	<0.03	1	0.3	<0.01	<0.02	25	7	3.5	-	1.5	0.25

The steels are normally supplied as proprietary alloys in accordance with UNS specifications:

	UNS		EN
Zeron 100 (Weir Materials)	S32760 (wrought)	J93380 (cast)	1.4507
DP3W (Sumitomo)	S32740	J93370	
SD40 (Meighs)	S32520		1.4501
UR52N+ (Industeel)	S32550		

These steels are always solution treated followed by quenching to give an approximately 50% austenite, 50% ferrite duplex structure without any deleterious phases such as sigma. They have a typical PREn value of >40. Tungsten is believed to improve pitting resistance and, if included, the PREw value will often exceed 40.

Background

Superduplex steels were developed in the 1970s to not only meet the demands of the offshore oil and gas industry for improved performance in more aggressive environments, but also provide much improved corrosion resistance in a number of acid environments. The role of copper in austenitic stainless steels such as 904L types (F–2) was already well established, and similar benefits can be gained with superduplex stainless steels. Tungsten is an addition in some of the grades, which increases strength and further improves corrosion resistance.

Performance

These steels offer the following:

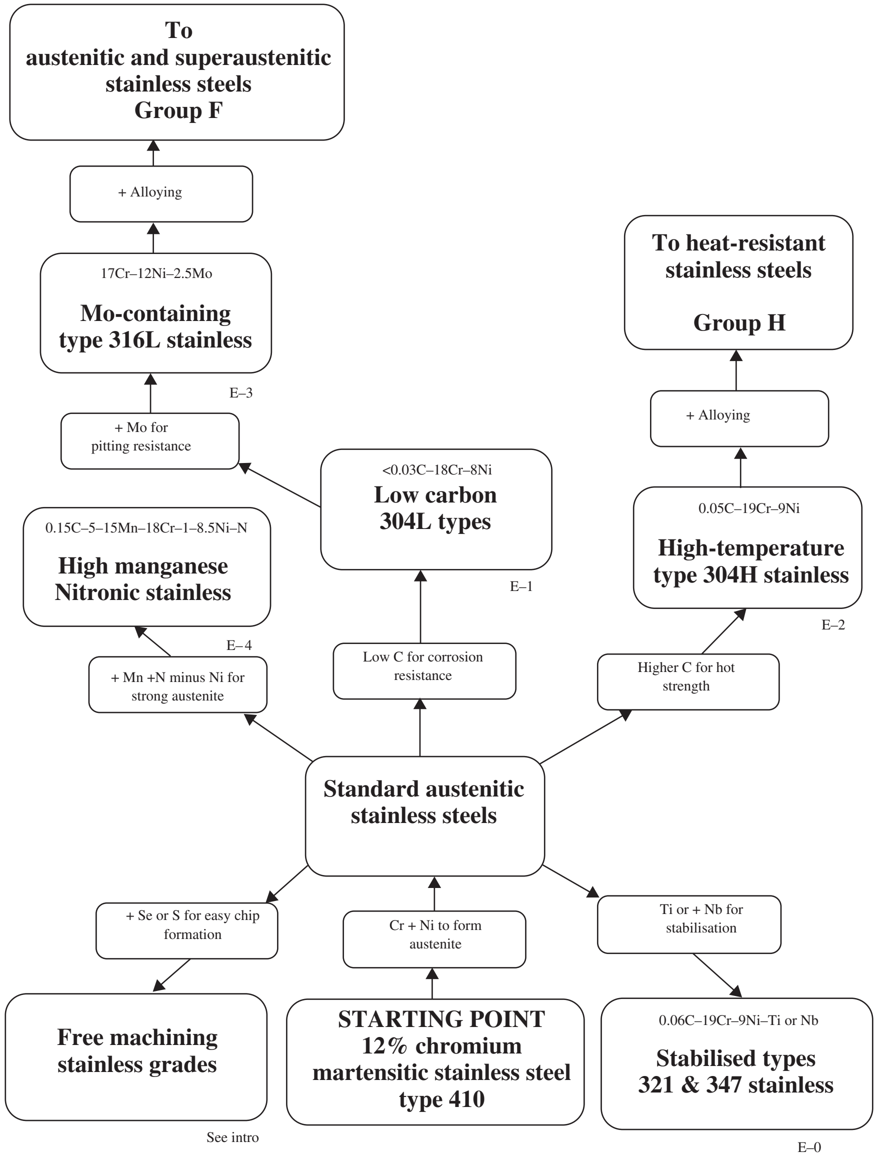
- Very high strength – much more than twice that of standard austenitic grades such as 316L, and about 10% higher than copper and tungsten-free 2507 superduplex grades (D–2).
- Very good general corrosion resistance in a wide range of aggressive acid environments.
- High resistance to chloride-induced SCC because of their high ferrite content, plus moderate resistance to hydrogen sulphide-induced SCC.
- High resistance to pitting attack in more aggressive chloride environments, e.g. seawater at higher temperatures.

Applications

The offshore oil and gas industry is a major user of these alloys. Applications are much the same as for the standard 2205 types namely, process pipework, flow lines, risers, manifolds and seawater systems, etc. They are generally used where corrosion conditions are somewhat more aggressive or where operating temperatures are higher. However, because of their resistance to sulphuric, hydrochloric and phosphoric acids and to caustic alkalis at temperatures up to about 300 °C, they are increasingly used in the chemical and process industries. Typical applications are desalination plants, flue gas desulphurisation (FGD) components and hot acid leaching and processing of metal ores.

Group E

Standard austenitic stainless steels



Group E: Standard austenitic stainless steels.

Introduction

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 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 is 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, 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 %	**Grade 216L**	>0.03	8.5	0.5	<0.01	<0.02	19	6	2.5	0.35
	Nitronic 60	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
Grade 216L	S21603	Gr. 216L
Nitronic 60	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.

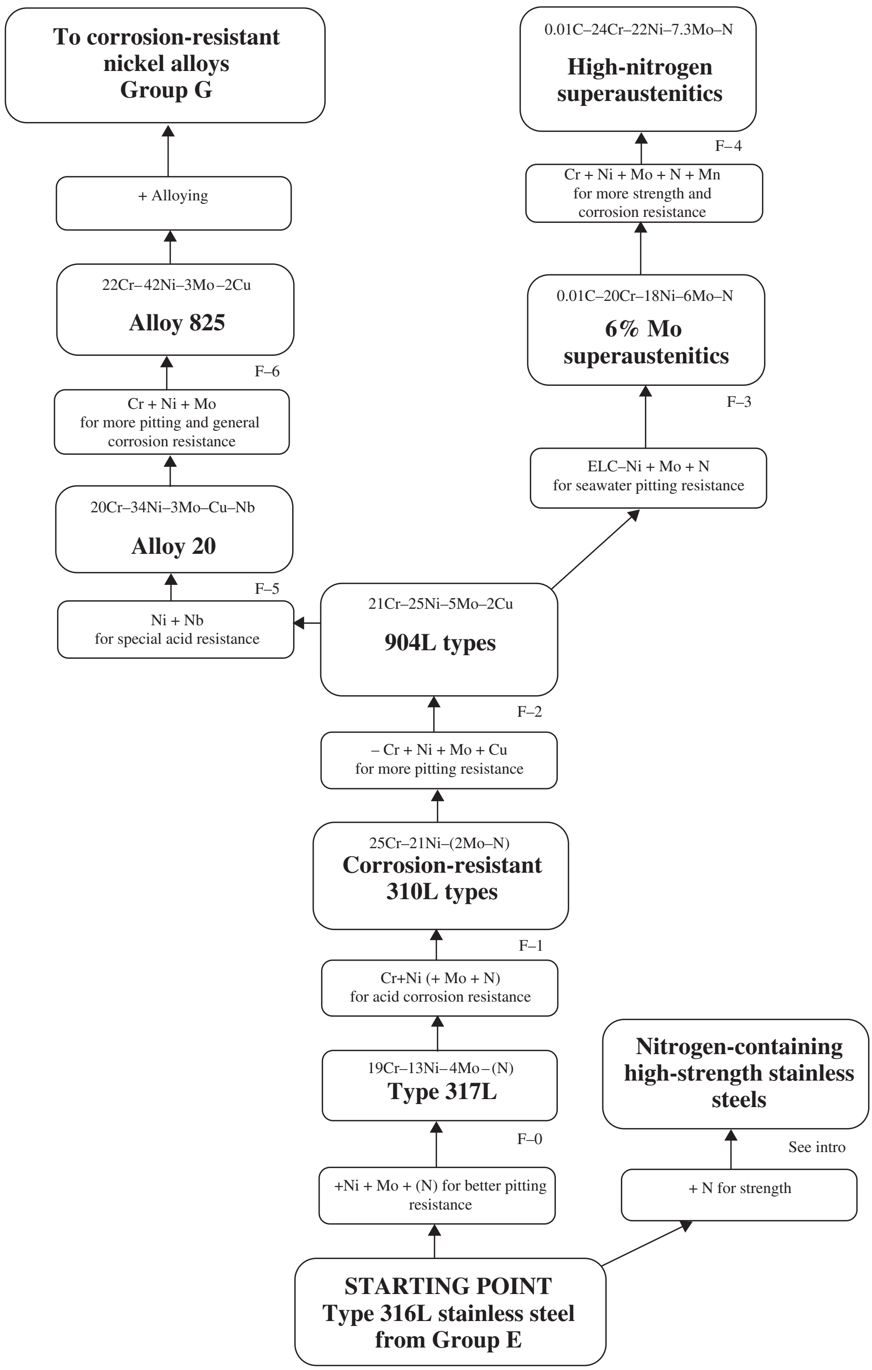
A major application, also in the USA, has been in the manufacture of spent nuclear fuel storage containers. Considerations were corrosion resistance in underwater ponds combined with high strength and consequent weight saving. Parts of the assembly subject to metal-to-metal contact were made from an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

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

Group F

Austenitic and superaustenitic stainless steels



Group F: Austenitic and superaustenitic stainless steels.

Introduction

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 superaustenic 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 firewater 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 %	**654 SMO**	<0.02	3	0.5	<0.01	<0.02	24	22	7.5	0.5	-	0.5
	UR B66	<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 superaustenic 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.

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 %	**Alloy 20**	<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.

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 %	**Alloy 825**	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 Nicrofer 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.

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.

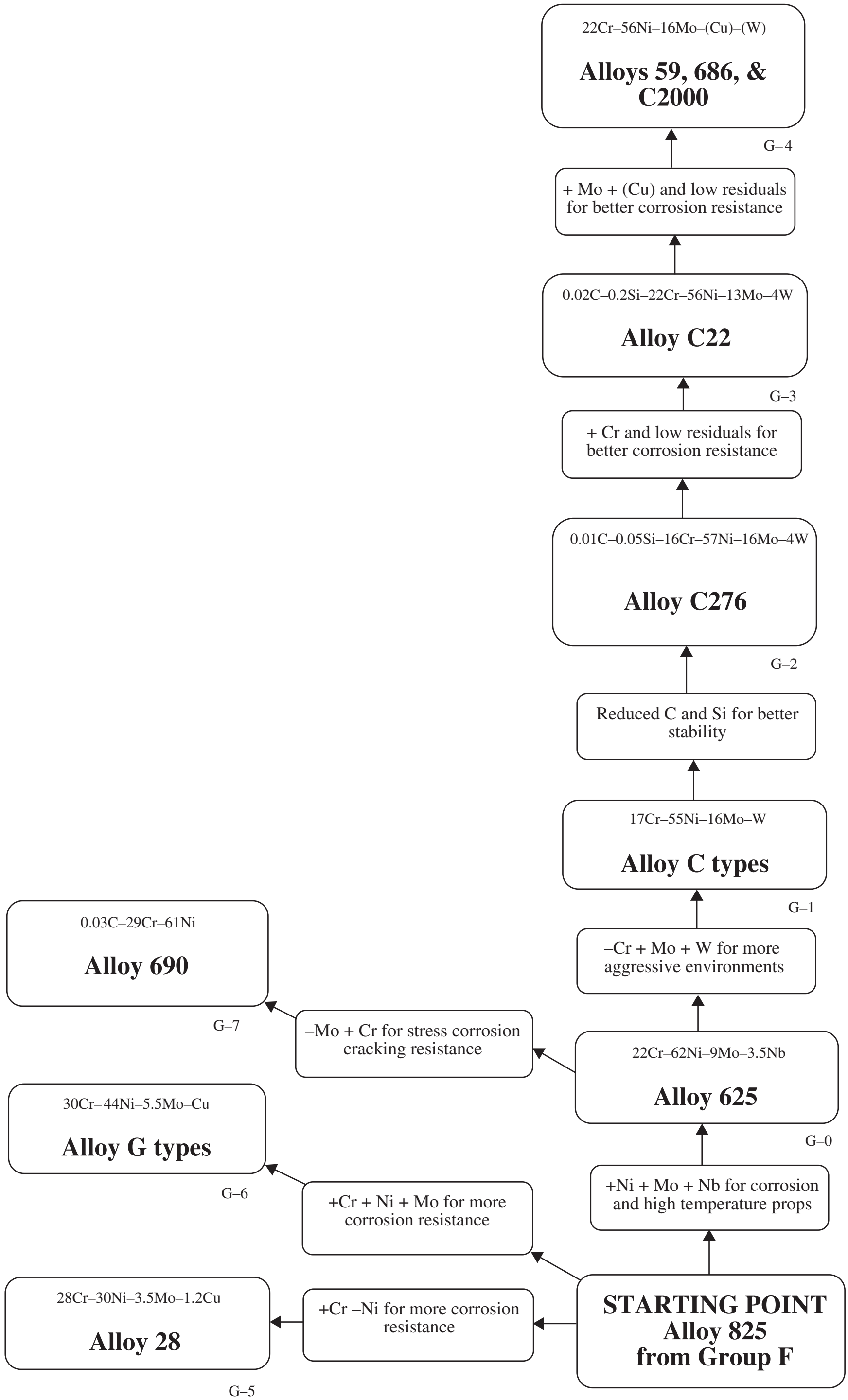
Nickel alloys, including 825, are generally stronger than most of the simple austenitic stainless steels and the resulting reductions in wall thickness and weight go some way to mitigate the significant cost increase arising from the high nickel content.

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.

Group G

Corrosion-resistant nickel alloys



Group G: Corrosion-resistant nickel alloys.

Introduction

Group G starts with alloy 825 from Group F and shows how much higher levels of critical alloying elements can be accommodated by the use of nickel rather than iron as the base element. In fact many of the alloys in this group contain little, if any, iron. The main branch in this group illustrates the evolution of some of the most corrosion resistant alloys currently available. This is achieved through careful balancing of high levels of chromium and molybdenum in combination with elements such as niobium, copper and tungsten, coupled with the latest production technology, which enables very low levels of both carbon and other undesirable residuals (e.g. sulphur and phosphorus) to be achieved.

There are three sub-branches, which illustrate alloy developments for somewhat specific rather than more general applications.

G–0

22% chromium, 62% nickel, 9% molybdenum, 3.5% niobium, nickel alloy

Also known generically as alloy 625

Description

This alloy has a significantly higher nickel and molybdenum content than alloy 825, with a corresponding cost premium. It also contains about 3.5% niobium, which is beneficial to both high-temperature properties and low-temperature strength and corrosion resistance. This is a virtually pure nickel alloy with a residual iron content of only 2 or 3%. A typical composition is:

		C	Mn	Si	S	P	Cr	Ni	Mo	Nb
Weight %	Alloy 625	<0.02	0.2	0.1	<0.01	<0.01	22	62	9	3.8

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
N06625	2.4856	Special Metals Inconel 625
A494 CW-6MC (cast)		VDM Nicrofer 6020hMo & 6022hMo

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

Background

This alloy with a high content of effective hardeners, namely molybdenum and niobium, was originally developed as a high-temperature alloy. However, since 1960, particularly in the offshore oil and gas industry, its virtually unique combination of strength and corrosion resistance at both high and low temperatures has made it increasingly popular where long-term performance and reliability more than outweigh the relatively high cost.

Performance

The addition of a much higher level of molybdenum, 9% in this alloy, broadens its range of resistance to include mineral acids and salts in both oxidising and reducing conditions. It has good to excellent corrosion resistance in virtually the complete range of inorganic and organic acids, as well as strong alkalis. The molybdenum also significantly improves resistance to pitting and crevice corrosion by wet chlorides.

Alloy 625 is also a strong material with a 0.2% proof strength in excess of 500 MPa at room temperature. This places it ahead of some duplex and most superaustenitic stainless steels. Finally, it has good elevated temperature rupture strength, but can suffer from long-term ageing, resulting in loss of ductility and toughness as precipitates form and grow, particularly at intermediate temperatures around 700 °C.

Applications

Alloy 625 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 most aggressive conditions for the manufacture and processing of a wide range of acids, alkalis and salts. For thick-walled vessels, where the cost of a solid structure might be prohibitive, carbon steel with a cladding of 625 is often used.

This technology has been widely exploited by the oil and gas industry since about 1975 and a wide range of components including valve blocks, christmas trees, flanges, flow lines and large separator vessels have been weld overlaid using alloy 625, often on a high-strength, low-alloy base material. This combines the economic, high strength to weight ratio performance of the base material with the resistance to pitting, crevice and stress corrosion of alloy 625. These components are now used for land-based as well as offshore topside and sub-sea applications where maximum performance and reliability are required.

G–1

17% chromium, 55% nickel, 16% molybdenum, 4% tungsten, nickel alloy

Also known generically as alloy C

Description

This alloy has a significantly higher molybdenum content than alloy 625, with a corresponding cost premium. It also contains almost 4% tungsten, which is beneficial to both high-temperature and low-temperature strength and corrosion resistance. This is a nickel alloy with a controlled iron content of about 5 or 6%. A typical composition is:

		C	Mn	Si	S	P	Cr	Ni	Mo	W	Fe
Weight %	Alloy C	< 0.05	0.5	1	<0.01	<0.01	17	55	16	4	6

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

UNS/ASTM	EN	Proprietary alloy
CW-12MW(cast)	2.4483	Haynes Hastelloy C

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

Background

This alloy was developed in the middle of the 20th century primarily as a corrosion-resistant alloy for the then rapidly developing chemical industry. The high molybdenum content gives exceptional corrosion resistance in chloride environments and it has a higher pitting resistance than alloy 625. At the time it was developed, the carbon and silicon contents were quite high and, in combination with the molybdenum content, tended to give rise to undesirable intermetallic phases in weld HAZs. For this reason, improved low-carbon and silicon variants on alloy C have continued to be developed, particularly as wrought products, which can be readily welded and fabricated. Nevertheless alloy C is still produced as castings, which can be solution treated after weld repairs. Alloy C can be considered as the forerunner of a family of high-performance corrosion-resistant alloys.

Performance

The addition of a much higher level of molybdenum, 15% in this alloy, broadens its resistance to general corrosion, pitting attack and stress corrosion in chloride environments, including seawater. The molybdenum and tungsten provide a reasonable degree of solid solution strengthening, which means that the alloy has good resistance to wear and abrasion.

Applications

This alloy is still used in the chemical industry, although for many applications it has been superseded by the more modern and advanced alloy C variants. Its use is now restricted to castings, particularly for pumps and valves handling slurries of chlorides and hypochlorites where its inherent hardness and abrasion resistance offer better performance than the low-carbon, low-silicon variants.

In extreme cases it has also been used for the manufacture of marine propellers for craft operating in polluted marine estuaries with high silt content. In these situations the combination of corrosion and abrasion resistance can justify the high initial cost when compared with the more traditional alloys such as aluminium bronze.

G–2

16% chromium, 57% nickel, 16% molybdenum, 4% tungsten, nickel alloy

Also known generically as alloy C-276

Description

This alloy has essentially the same basic composition as alloy C, but modern production methods have enabled both the carbon and silicon levels to be controlled to very low levels. A typical composition is:

		C	Mn	Si	S	P	Cr	Ni	Mo	W	Fe
Weight %	Alloy C-276	<0.01	0.8	0.05	<0.01	<0.01	16	57	16	4	6

This alloy is produced primarily as wrought material and is supplied in accordance within one of the following specifications:

UNS/ASTM	EN	Proprietary alloys
N10276	2.4483	Haynes Hastelloy C-276 Most nickel alloy producers offer an ‘alloy 276’

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

Background

This alloy was developed in the 1970s to meet the demand from the chemical and pharmaceutical industries for a versatile corrosion-resistant alloy that would be available in a range of wrought product forms and that could be readily fabricated and welded without serious loss of corrosion resistance and without the need for post-weld solution heat treatment. Alloy C-4 is similar in composition to C-276, but contains no tungsten. It has similar corrosion resistance but improved high-temperature stability and resistance to ageing at temperatures up to 1050 °C.

Performance

The overall corrosion resistance of alloy C-276 is similar to alloy C except that the stringent control of carbon and silicon minimises the risk of grain boundary precipitates forming in weld HAZs, with a consequent reduction in the risk of corrosion.

Alloy C-276 has exceptional resistance to localised corrosion and to both oxidising and reducing media. It is resistant to acids, acid salts and a wide range of aggressive organic and inorganic compounds encountered during chemical processing, over a wide range of temperatures.

It is particularly resistant to attack by wet chlorine and hypochlorites, and the high molybdenum content ensures resistance to chloride-induced pitting and crevice corrosion.

Applications

This alloy is probably the most widely used of all the corrosion-resistant nickel alloys. In the chemical and pharmaceutical industries it is used for the fabrication of pipework, process vessels, heat exchangers and tanks. Most thin-walled fabrications are made from solid C-276 but for larger, thicker-walled vessels, carbon or low-alloy steels clad with a few millimetres of C-276, can be used with a consequent reduction in material costs.

Because of its versatility, it is sometimes used as a 'catch-all' material where the operating environment is not well defined or may be subject to unpredictable changes. It is also used in flue gas scrubbers, where its resistance to sulphur-contaminated, wet acid chlorides is very good. However, for some of the most demanding applications it has been overtaken by more modern, improved alloy C variants, for example those listed on G–4.

The offshore oil and gas industries exploit C-276 for components subjected to extreme risk of pitting and crevice corrosion in areas where inspection and maintenance are difficult. Examples are flanges and valves in sub-sea well-head installations and clad sub-sea pipe bundles. Here the performance of C-276 is superior to alloy 625, because of the increased molybdenum content. It is also preferred to alloy 625 in oil and gas environments with high sulphur, high carbon dioxide at temperatures up to about 250 °C.

G–3

22% chromium, 56% nickel, 13% molybdenum, 3% tungsten, nickel alloy

Also known generically as alloy C-22

Description

This alloy has a somewhat similar composition to alloy C-276 but has a significantly higher chromium content at 22%, combined with small reductions in molybdenum, tungsten and residual iron. The net effect on pitting resistance in chloride media is effectively neutral. A typical composition is:

		C	Mn	Si	S	P	Cr	Ni	Mo	W	Fe
Weight %	Alloy C-22	<0.01	0.4	0.05	<0.01	<0.01	22	56	13	3	3

The alloy is produced primarily as wrought material and is supplied in accordance within one of the following specifications:

UNS/ASTM	EN	Proprietary alloys
N06022	2.4602	Haynes Hastelloy C-22
CX2MW	2.4811	VDM Nicrofer 5621hMoW
		Special Metals Inconel 622

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

Background

This alloy was introduced about 1980 by Haynes International (formerly Cabot Alloys) as a development and improvement on alloy C-276 for certain applications. Until recently it was protected by a patent. However, the patent has now expired and a number of nickel alloy producers worldwide offer their own versions of alloy C-22.

Performance

The overall corrosion resistance of alloy C-22, including resistance to pitting, crevice corrosion and stress corrosion cracking, is similar to alloy C-276.

However, the increase in chromium content improves the performance in a wide range of oxidising media. It is effectively immune to attack in a wide range of chemical process environments such as ferric and cupric chlorides, hot contaminated media (organic and inorganic), chlorine, formic and acetic acids, acetic anhydride and seawater and brine solutions.

Applications

Now that the alloy is more widely available from a number of producers, it is finding a range of applications in the chemical and pharmaceutical industries. It is used for the fabrication of pipework, process vessels, heat exchangers and tanks. Most thin-walled fabrications are made from solid C-22, but for larger, thicker-walled vessels, carbon or low-alloy steels clad with a few millimetres of C-22 can be used with a consequent reduction in material costs.

Because of its versatility, it is sometimes used as a 'catch-all' material where the operating environment is not well defined or may be subject to unpredictable changes. It is used in flue gas scrubbers and other components where its resistance to sulphur-contaminated, wet acid chlorides is very good and offers improvements over alloy C-276.

It is also used in chlorination, bleaching and dye plants in pulp and paper and textile manufacture. An interesting, but rather limited, use is in the construction of geothermal wells, where the alloy is able to withstand the corrosive effects of steam and water severely contaminated with sulphur, chlorides and other salts.

G–4

22% chromium, 16% molybdenum, nickel alloys, with and without copper and tungsten

Also known generically as alloy C-2000, alloy 59 and alloy 686

Description

These are some of the most highly alloyed corrosion-resistant nickel alloys commercially available. They combine high chromium content at about 22% and high molybdenum at about 16%. Alloy C-2000 contains a little less than 2% copper and alloy 686 contains approximately 4% tungsten. Typical compositions are:

		C	Mn	Si	S	P	Cr	Ni	Mo	W	Cu
Weight %	**Alloy C-2000**	<0.01	0.4	0.05	<0.01	<0.01	23	59	16	-	1.6
	Alloy 59	<0.01	0.2	0.03	<0.01	<0.01	23	60	16	-	-
	Alloy 686	<0.01	0.2	0.05	<0.01	<0.01	21	58	16	4	-

These alloys are produced primarily as wrought material and are supplied in accordance within one of the following proprietary specifications and UNS numbers:

UNS	Proprietary alloys
N06200	Haynes International Hastelloy C-2000
N06059	VDM Nicrofer 5923hMo
N06686	Special Metals Inconel 686

The alloys are always solution treated followed by rapid quenching to give a stable fully nickel-base austenitic structure.

Background

These alloys have been made since about 1980 by a number of the leading nickel-based alloy producers and represent the current state of development of corrosion-resistant alloys designed to resist a wide range of highly aggressive environments. Each alloy represents an attempt to combine resistance to both oxidising and reducing environments and still retain metallurgical stability.

Performance

The producers make various claims as to the superiority of their own particular alloy and these may well be valid for certain specific environments. In particular, the addition of tungsten in one case and copper in another will provide some benefits. Nevertheless, all the alloys offer outstanding corrosion resistance under a wide range of conditions. The high chromium contents are required to provide resistance to oxidising media, such as when ferric ions, cupric ions or dissolved oxygen are present. Reducing environments, however, such as dilute hydrochloric or sulphuric acids require high molybdenum and tungsten. All of these alloys offer exceptional resistance to pitting, crevice and stress corrosion cracking, particularly in chloride environments. Finally, they are virtually immune to attack by high-sulphur, high-chloride and low pH condensates at elevated temperatures.

Applications

The relatively high cost of these alloys means that they are used only in the most critical of applications where other corrosion-resistant nickel alloys have failed or do not provide an economic life. The major users are in the chemical industry and the alloys are fabricated into a wide range of process plant. They are used in digesters for pulp and paper manufacture and in the offshore oil and gas industries for the most critical of applications where reliability is paramount.

One of the most important applications is in FGD equipment, particularly as a thin 'wallpaper' to provide protection to gas ducting from the extreme corrosion conditions formed by condensates from flue gases. There are few alloys suitable for this most aggressive environment and alternative materials, such as rubber lining, have proved unsatisfactory.

G–5

28% chromium, 30% nickel, 3.5% molybdenum, 1% copper plus nitrogen, nickel alloy

Also known generically as alloy 28

Description

This alloy is closely related to alloy 825 (F–6), although it has a higher chromium content of about 28%. The iron content just exceeds the nickel content at a little over 30%. As with alloy 825 it is debatable as to whether this should be grouped with the highly alloyed superaustenitic stainless steels or as a nickel alloy. However, since it is a development of alloy 825 and has a similar total alloy content, it is has been placed with the corrosion-resistant nickel alloys in Group G. A typical composition is:

		C	Mn	Si	S	P	Cr	Ni	Mo	Cu	N
Weight %	Alloy 28	<0.02	2.0	0.7	<0.01	<0.02	27	31	3.5	1.2	0.05

The 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
N08028	1.4563	Special Metals Incoloy 28 VDM Nicrofer 3127LC Sandvik Sanicro 28

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

Background

This alloy is a further development of alloy 825 (F–6) with the aim of achieving better corrosion resistance in mineral acids and improved pitting resistance. This is achieved by increasing both the chromium and molybdenum contents. However, the nickel content is reduced somewhat and this makes the alloy particularly cost competitive when compared with the more highly alloyed nickel alloys. The alloy also contains a small nitrogen addition, which provides some modest strengthening over nitrogen-free austenitic alloys.

Performance

The alloy has good resistance to a variety of corrosive media such as contaminated mineral acids and organic acids, including exceptional resistance to phosphoric acid particularly when containing halide impurities. It has excellent resistance to pitting, crevice and intergranular corrosion. The relatively high nickel content also ensures high resistance to SCC, particularly in chloride and hydrogen sulphide environments. The PREn value is about 36–38 and the alloy is resistant to flowing seawater. It also has good mechanical properties with about 10% extra tensile strength when compared with other similar alloys without nitrogen additions, e.g. alloys 825 and 20 (Group F). It can be further strengthened by cold working.

Applications

Alloy 28 is used extensively by the chemical industry in acid production. In the 'wet' process for the production of phosphoric acid, materials are subject to corrosion by halide impurities in the phosphate ore. Alloy 28 has been found to be one of the most resistant austenitic alloys and is widely used in the digestion and filtration stages of the process.

It is used in overhead condensers in oil refineries, particularly in areas subject to chloride and sulphide contamination. It is also suitable for tubing and heat exchangers handling sulphuric acid contaminated with chlorides and for seawater piping and condensers.

Finally it finds application in the offshore oil and gas industry as production tubes, casings and liners in deep sour-gas wells where it is used in the cold-worked condition to give high mechanical strength combined with corrosion resistance.

G–6

30% chromium, 44% nickel, 5.5% molybdenum, 2% copper plus tungsten and niobium, nickel alloy

Also known generically as alloy G-30

Description

This alloy has a similar nickel content to alloy 825, but with a significantly higher level of chromium, molybdenum plus additions of tungsten and niobium to give improved corrosion performance in a wider range of acid media. In this respect the alloy represents something of a mid-point, in terms of both performance and cost, between 825 (F–6) and the much more highly alloyed 625 (G–0) and alloy C type (G–2 to G–5) compositions. A typical composition is:

	C	Mn	Si	S	P	Cr	Ni	Mo	Cu	W	Nb	Fe
Weight %	0.02	0.3	0.3	<0.01	<0.02	30	44	5.5	2	1.7	2	15

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

UNS/ASTM	Proprietary alloy
N06030	Haynes Hastelloy G-30

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

Background

This alloy was originally developed as a casting alloy, Hastelloy G, for acid-resistant pumps and valves for use in the chemical industry. As demand grew for a range of wrought materials to widen the scope of applications, alloy G-3 with lower carbon content was introduced. Within the 1990s, a further development in the form of alloy G-30 was introduced. This has a higher chromium content (30%) but reduced molybdenum and niobium and increased tungsten. These changes to the composition are claimed to improve weldability and particularly to increase corrosion resistance by reducing segregation and precipitation in weld HAZs. Hastelloy G-30 has now totally superseded alloy G-3.

Performance

This alloy is designed to have better acid corrosion resistance than alloys 400 (J–1), 600 (I–1) and 825 (F–6), particularly in sulphuric and contaminated phosphoric acids. It can also withstand both oxidising and reducing conditions. It offers reasonable corrosion resistance in hydrochloric acid but like alloy 825 tends to suffer from chloride pitting and crevice corrosion, particularly in stagnant, unaerated solutions. The relatively high iron content (approximately 20%) for a nickel alloy means that it is less resistant to halogens and alkalis than some of the more highly alloyed grades.

In other environments, for example those related to the oil and gas industry, these alloys offer no real advantage over alloy 825.

Applications

This alloy is used primarily 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. As processing temperatures and pressures have increased, combined with a need for increased plant life and reliability, the demand for specialised alloys tuned to meet specific requirements has increased. However, these are special alloys with a fairly limited range of economic applications and are therefore only available from a few suppliers.

G–7

29% chromium, 61% nickel, nickel alloy

Also known generically as alloy 690

Description

This alloy is quite a simple system with about 60% nickel, 30% chromium and the balance iron. It has one of the highest chromium contents of any of the nickel alloys available in wrought form and suitable for the fabrication of pressure equipment. It does not contain any molybdenum. A typical composition is:

		C	Mn	Si	S	P	Cr	Ni
Weight %	Alloy 690	<0.02	0.2	0.1	<0.01	<0.01	29	61

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

UNS/ASTM	EN	Proprietary alloys
N06690	2.4642	Special Metals Inconel 690 VDM Nicrofer 6030

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

Background

This alloy was developed in the last few decades of the 20th century to operate in some quite specific high-temperature environments encountered in both the chemical and nuclear industries. It was not designed to have good pitting and crevice corrosion resistance in chloride environments and this is reflected in the complete lack of molybdenum and tungsten in the alloy composition.

The high chromium content improves corrosion resistance in hot sulphidising environments.

Performance

The high chromium content of about 30% confers exceptional resistance to oxidising media at high temperatures. It also improves the resistance to SCC at high temperatures in water-based cooling systems, and in this respect alloy 690 offers significant improvements over alloy 600 (I–1) with a higher nickel content (75%) and lower chromium content (21%).

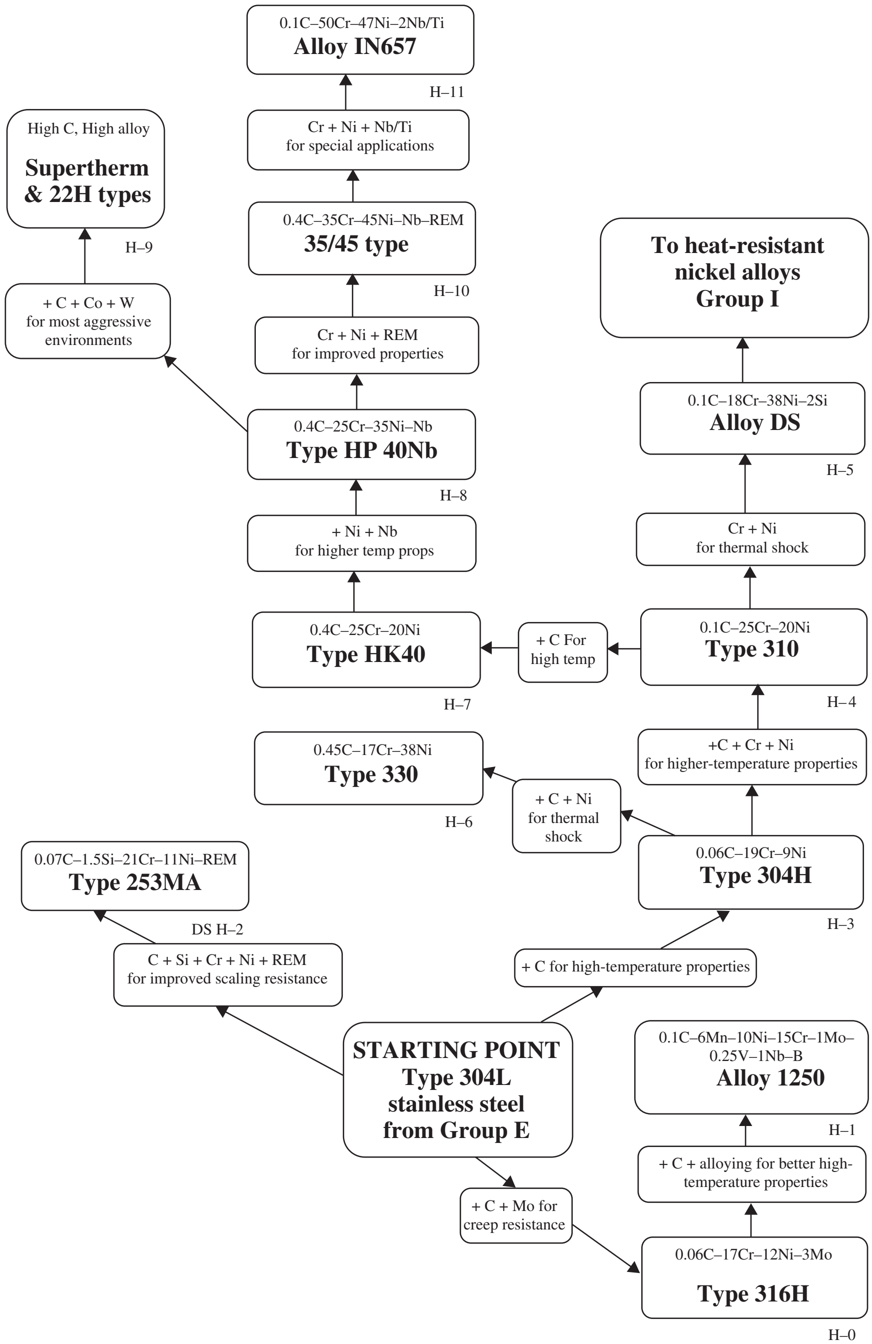
Applications

Alloy 690 is used selectively by the chemical industry in the form of tanks, process vessels, pipework systems and heat exchangers in the most aggressive conditions for the manufacture and processing of hot concentrated sulphuric, nitric and nitric/hydrofluoric acid mixtures as well as acid salts.

It is increasingly being used as an alternative to alloy 600 for heat exchanger and steam generator construction in pressurised water nuclear reactor systems both in the construction of new units and in replacement units where these have suffered from severe SCC in the past. Since this is a relatively new alloy, it is likely that further applications will be developed.

Group H

Heat-resistant stainless steels



Group H: Heat-resistant stainless steels.

Introduction

Group H starts with type 304L stainless steel from Group E and is a rather complex group with several branches and sub-branches reflecting a number of different design philosophies adopted to achieve specific high-temperature properties for particular applications. The main branch shows the evolution of controlled carbon austenitic stainless steels with increasing alloy content. When the nickel and iron contents are approximately the same at around 40%, the distinction between stainless steels and nickel alloys becomes blurred. This is exactly analogous to the corrosion side of the alloy tree. In the case of high-temperature alloys, alloy DS represents the transition point and the link to Group I heat-resistant nickel alloys.

A major branch is that which shows the development of high carbon, typically 0.4%, austenitic stainless steels. Some of the more highly alloyed types contain significantly more nickel than iron and strictly should be classified as nickel alloys. However, they have evolved progressively from stainless steels, are used for similar applications and are generally available only as castings. For these reasons they are properly included in Group H. In fact, the most highly alloyed material described is approximately 50% chromium and 50% nickel with no iron content at all!

There are two sub-branches. One deals with molybdenum-bearing high-temperature alloys and the other with alloys that make use of rare earth metal (REM) additions to improve oxidation and scaling resistance in high-temperature gaseous environments.

H–0

Controlled carbon, 17% chromium, 12% nickel, 2.5% molybdenum austenitic stainless steel

Also known generically as type 316H

Description

This steel is the high-temperature version of type 316 with a similar composition, but with carbon content controlled in the range 0.04 to 0.08% to give improved high-temperature properties, particularly creep resistance. A typical composition is:

	C	Mn	Si	S	P	Cr	Ni	Mo
Weight %	~0.06	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
S31609	Gr. 316H CF10M (castings)

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

Background

Stainless steels have always been of interest as high-temperature alloys since they combine long-term thermal stability with good corrosion resistance, particularly high-temperature oxidation and scaling resistance, helped by the high chromium content. However, they also have a number of disadvantages, not least of which is their high cost compared with low-alloy creep-resisting steels. They also have high coefficients of expansion, which can cause problems when used with other steels and they have low coefficients of thermal conductivity, which can limit their use in thick sections. Nevertheless, 316H is quite widely used for a number of high-temperature applications.

Performance

This steel combines good corrosion resistance with long-term creep resistance and thermal stability. However, 316H is not a particularly strong alloy and a number of related alloys have been developed to improve creep strength, particularly at higher temperatures. A typical operating temperature range for 316H would be 500–800 °C.

Corrosion resistance is reasonable and similar to type 316L. However, the higher carbon content, combined with the absence of stabilisation, increases the risk of weld HAZ attack under certain conditions.

Applications

Type 316H is mainly used for high-temperature plant and components in thermal and nuclear power stations and in the chemical and petrochemical industries. It tends to be used for plant and components operating at higher temperatures where the additional cost can be justified. It also tends to be used in thinner sections if thermal expansion and conductivity issues are important. Specific applications include steam piping, superheater headers, furnace parts and some gas and steam turbine components.

H–1

15% chromium, 10% nickel, 1% molybdenum, 6% manganese, austenitic stainless steel with vanadium, niobium and boron additions

Also known generically as alloy 1250

Description

This steel is a complex austenitic creep-resisting steel with a composition designed to optimise long-term high-temperature creep performance. The steel has a moderate carbon content and additions of vanadium, niobium and boron to give stable carbides as long-term ageing takes place within an austenitic structure stabilised with both nickel and about 6% manganese. A typical composition is:

	C	Mn	Si	S	P	Cr	Ni	Mo	V	Nb	B
Weight %	0.1	6	0.5	<0.01	<0.02	15	10	1	0.25	1	0.005

The steel is normally supplied in accordance with:

UNS
S21500

The steel is usually solution treated, followed by quenching, to give a fully austenitic structure. Tubes are often supplied in the warm worked condition.

Background

The then private steel company Samuel Fox Ltd, based near Sheffield, developed this steel in the 1960s. The company became part of the English Steel group and the steel was designated Esshete 1250. It was one of a number of complex austenitic creep-resisting alloys developed at the time to provide enhanced performance in supercritical thermal power stations then being built in large numbers.

Performance

This steel is designed for long-term continuous service at temperatures up to 675 °C. It combines a high level of rupture strength with reasonable ductility and good weldability. It also has excellent structural stability and good oxidation resistance because of the high chromium content. At the time it was designed for use in the most advanced power stations operating with high steam temperatures at about 600 °C.

Applications

This steel is used almost exclusively in fossil-fuelled power stations. It finds application in pressure parts, superheaters and steam pipes. It is also used for turbine blades, valve covers and high-temperature bolting.

Its high resistance to oxidation and high-temperature scaling is exploited in coaxial tubing. It is used as the outer layer of co-extruded tubing and piping, in conjunction with low-alloy creep-resisting steels, which are much cheaper and have better thermal conductivity. However, they do not have sufficient oxidation resistance at the higher temperatures and are therefore 'protected' by an outer layer of alloy 1250.

H–2

21% chromium, 11% nickel, austenitic stainless steel with controlled carbon content, silicon, nitrogen and REM

Also known generically as type 253MA

Description

This steel is the most widely used of a group of austenitic stainless steels specifically designed to combine good high-temperature properties and scaling resistance with economy of alloy content. A slightly enriched type 304H composition is further enhanced by the addition of somewhat more carbon plus silicon, nitrogen and REMs. A typical composition is:

		C	Mn	Si	S	P	Cr	Ni	N	REM
Weight %	**Type 253MA**	0.08	1	2	<0.01	<0.02	21	11	0.15	~0.01

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

UNS/ASTM	EN	Proprietary alloy
S30815	1.4835 1.4893	Avesta Polarit 253MA

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

Background

This is one of a series of steels introduced by Avesta Steel (now Avesta Polarit) since about 1970. The leanest alloyed is 153MA and this is essentially a type 304 with additions of nitrogen to increase strength and a higher silicon content plus REM additions to improve high-temperature oxidation resistance. Type 253MA, the most well-known and widely used grade, has slightly higher carbon, chromium and nickel contents to improve overall performance. The highest alloyed grade, type 353MA, is based on the 25% chromium, 35% nickel system and provides further improvements in performance, albeit at a significantly higher cost. All three alloys contain high silicon with nitrogen and REM additions.

Performance

This steel is designed to give creep strength and resist serious oxidation at temperatures in the range 900–1100 °C. The addition of nitrogen improves strength. The high silicon content and the REM additions act synergistically to stabilise the oxide film and so prevent oxide spalling and long-term progressive degradation.

Resistance to sulphidation under oxidising conditions is superior to many higher nickel heat-resisting alloys. In addition, resistance to carburisation and nitriding is reasonable, except under reducing conditions where higher nickel alloys are superior.

These alloys are not primarily designed to provide good corrosion resistance under aggressive aqueous conditions.

Applications

Alloy 253MA has found worldwide use in a wide range of industries. Components manufactured from the steel include burner tubes, hot gas cyclones, hot gas recuperators, calcining and muffle furnaces, hot gas ducting and fans. These are used extensively in plant manufacturing cement, iron and steel and other metals and ceramics.

In recent years the alloy has been used in modern power generation plant for piping, ducting and cyclones that are in direct exposure to hot exhaust gases. It can also be used to manufacture refractory anchor bolts, where its high resistance to oxide formation reduces the risk of damage to and cracking of the heat-resistant refractory lining.

It is not generally found in the chemical and petrochemical industries, where conditions tend to require the use of more highly alloyed materials than 253MA.

H–3

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

Also known generically as type 304H

Description

This steel is the same as the ubiquitous type 304L with the exception that is 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 %	~0.06	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

This steel is 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 or even very low carbon, 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 the corrosion resistance is not particularly good and precautions have to be taken to avoid corrosive acid condensates, which may form at low temperatures during shut down of catalytic cracking processes and could 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.

H–4

Medium carbon, 25% chromium, 20% nickel, austenitic stainless steels

Also known generically as type 310

Description

These steels are a simple alloy of 25% chromium and 20% nickel with a carbon content usually in the range 0.1–0.25%. They should not be confused with the cast 0.4% carbon versions known as HK40 (H–7), nor with the very low-carbon versions that are designed for corrosion resistance (F–1). They can be supplied as both wrought and cast products. A typical composition is:

		C	Mn	Si	S	P	Cr	Ni
Weight %	**Type 310**	~0.15	1	0.5	<0.01	<0.02	25	20

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

UNS/ASTM	EN	Proprietary alloys
S31000	1.4840, 1.4841	Firth Vickers Immaculate 5
Gr. 310 CK20 (cast)	1.4842, 1.4845	CLI Sirius 3
		Sandvik 15RE10

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

Background

These steels were some of the first generation industrial stainless steels and their origin can be traced back to the early 18/8 austenitic steels. The design philosophy was simple: the carbon was increased to improve hot strength, and the chromium was raised to 25% to provide good high-temperature scaling resistance. In order to maintain a fully austenitic microstructure and avoid ferrite, which would transform to sigma during long-term service, the nickel content was increased to 20%.

Performance

Type 310 provides good scaling resistance in clean air or oxygen at temperatures up to about 1100 °C. However, prolonged exposure above 1000 °C, particularly if thermal cycling or fatigue is also present, will result in breakdown and spalling of the oxide film, resulting in premature failure. Nevertheless, iron–nickel–chromium alloys are a common choice for many high-temperature applications because of their relatively low cost, good mechanical properties, moderate oxidation resistance and ready availability in a wide range of product forms.

Applications

Type 310 alloys are invariably used for heat-resistant applications such as furnace parts, heat shields, hot gas ducting and cyclones. The main industrial users are iron and steel, cement, ceramic and metal producers. While this is still an important alloy, many of its uses have been substituted by more modern alloys such as Avesta 253MA (H–2), which tend to be much lower in nickel content and hence lower in price and, with their higher silicon content plus REM additions, offer better long-term oxidation resistance.

H–5

Low carbon, 18% chromium, 38% nickel, 2% silicon, austenitic stainless steels

Also known generically as alloy DS

Description

This alloy is closely related to alloy 330 (H–6). However, the high-carbon version of alloy 330 is only available as castings and has a carbon content of about 0.45%, similar to HK40 (H–7). This is a simple, low-carbon alloy with about 18% chromium, 38% nickel, 2% silicon and an iron content of 40%. For the purposes of grouping, this alloy is included with the high-temperature austenitic stainless steels. However, the iron and nickel contents are similar and this alloy represents the transition point between high-temperature stainless steels and nickel alloys, and is the starting point for Group I. A typical composition is:

		C	Mn	Si	S	P	Cr	Ni	Fe
Weight %	**Alloy DS**	0.05	1	2.2	<0.01	<0.02	18	38	40

The alloy is normally supplied in accordance within one of the following specifications, but it should be noted that different proprietary alloys might have slightly different compositions:

ASTM/UNS	EN	Proprietary alloys
N08330	1.4862	Special Metals Incoloy DS Rolled Alloys RA330

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

Background

These type 330 alloys (H–6) were first developed as high-carbon castings about the middle of the 20th century. However, wrought versions were later developed to widen the available range of product forms and hence the scope of applications. In order to facilitate the hot working of these alloys to produce plate, sheet and wire, etc., the carbon level is reduced to levels below 0.1%. In fact, alloy DS was specifically developed by Inco for woven wire furnace conveyor belts.

Performance

Alloy DS is designed as a high-temperature alloy with good mechanical strength up to 1050–1100 °C and reasonable scaling resistance, being achieved with the combination of 18% chromium and about 2% silicon. It is also resistant to ‘green rot’, which can occur in nickel–chromium alloys when furnace atmospheres vary between reducing and oxidising, and in some cases where there is a carburising atmosphere. Under these conditions, chromium carbides can form along the grain boundaries and preferential oxidation of the chromium-depleted matrix, then takes place. Alloy DS is also resistant to sigma formation, and consequent embrittlement, and can be heated in the critical 600–900 °C range, for indefinite periods of time.

Applications

Apart from its original use for woven wire furnace conveyor belts, alloy DS is widely used for a range of heat treatment applications where its strength and corrosion resistance at high temperature enable it to be used in light sections. Major uses include high-temperature process equipment and fittings, furnace retorts and heat treatment jigs. It is also used for some high-temperature components in general industrial and domestic equipment.

H–6

High carbon 17% chromium, 38% nickel, austenitic stainless steel

Also known generically as type 330 or HT

Description

These steels are quite closely related to the HK40 alloys (H–7), in that the cast version has a carbon content of about 0.45%, similar to HK40. These are simple alloys with about 17% chromium and 38% nickel. They are variously described by different users as 17/38 or 38/17 alloys, depending on which of the two major alloying elements is considered the more important. The low carbon wrought version, often known as alloy DS, is described in H–5. A typical composition is:

		C	Mn	Si	S	P	Cr	Ni
Weight %	**Type 330**	0.45	1	1.5	<0.01	<0.02	17	35

Note: HT has typical carbon content of 0.45%, whereas HT30 has about 0.3%.

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

UNS/ASTM		EN	Proprietary alloys
N08605	A297 HT	1.4865	Doncasters Paralloy H38, H40, H33 & H35
N08030	A351 HT30		Duraloy Thermalloy T50 & T58
			Rolled Alloys RA330-HC

These steels are always solution treated followed by quenching to give a stable fully austenitic structure. However, castings may contain pockets of ferrite, which may transform to sigma.

Background

These alloys were first developed as high-carbon castings about the middle of the 20th century. However, wrought versions were later developed to widen the available range of product forms and hence the scope of applications. In order to facilitate the hot working of these alloys to produce forgings, etc.. the carbon level is reduced to below 0.1% (H–5). Both cast and wrought versions contain significant amounts of silicon, sometimes in excess of 2%, and this improves oxidation resistance in certain environments.

Performance

Type 330 alloys are designed as high-temperature alloys with good mechanical strength up to 1050–1100 °C and reasonable scaling resistance, being achieved with the combination of 18% chromium and up to 2% silicon. However, the combination of the relatively high nickel content and the low coefficient of thermal expansion make these alloys particularly resistant to thermal shock.

The alloy is also highly resistant to carburisation and nitriding but is not suitable for use in high sulphur-bearing furnace atmospheres.

Applications

These alloys are used for heat treatment trays and baskets, furnace rollers, moulds and hearth plates and similar components that are subjected to repeated rapid heating and cooling cycles. A particular application is the manufacture of quench baskets that contain engineering components, which are heat treated above 1000 °C, and then the basket and contents are subject to rapid quenching. Type 330 alloy is one of the few materials that can withstand the repeated thermal shock imposed by this process.

H–7

0.4% carbon, 25% chromium, 20% nickel, cast austenitic stainless steels

Also known generically as type HK40

Description

These steels are like other 310 types in that they contain 25% chromium and 20% nickel, with the balance iron. However, unlike the plain 310 and the very low-carbon 310L types, they have a high carbon content of 0.4% and are generally only available as castings. A typical composition is:

		C	Mn	Si	S	P	Cr	Ni
Weight %	**Type HK40**	0.4	2	1	<0.01	<0.02	25	20

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

UNS/ASTM		EN	Proprietary alloys
J94204	A351 A608 Gr. HK40	1.4846	Doncasters Paralloy H20
J94224	A297 Gr. HK	1.4848	Duraloy Thermalloy 47
			Cronite HR6

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

Background

This alloy was developed about 1950, to meet the needs of the rapidly developing chemical and petrochemical industries and other users who required an economic high-temperature steel. For many years it was the workhorse alloy, but since 1975 better-performing alloys have been developed to meet increasingly arduous conditions. The combination of 25% chromium and 20% nickel with a high carbon level provides excellent high-temperature performance at a reasonable cost. These alloys were not developed for, and are not intended for, use in corrosive conditions.

Performance

Alloy HK40 is designed to operate for continuous long periods at temperatures of about 1000 °C. At almost 1100 °C it has a 100 000-hour (more than 10 years) rupture stress of about 4 MPa, combined with good oxidation resistance and reasonable carburisation resistance. These high-carbon cast alloys do not have good room temperature ductility, and after long periods of high-temperature service, further deterioration takes place as sigma and other intermetallic phases form. While the steel is readily weldable in the original as-cast condition, special precautions have to be taken when welding service-aged material.

Applications

The most well-known use of this alloy is in the manufacture of pyrolysis coils for use in high-temperature ethylene reformer and steam cracker plants. The coils consist of centrifugally cast tubes joined to conventionally cast bends and headers. The complete assemblies operate in a fired furnace at temperatures around 1000 °C at reasonably high pressures, often for many months continuously. With hydrocarbon feedstocks, carburisation of the alloy and coking of the tubes are recognised problems. Creep and creep fatigue are also causes of failure, and the need to improve service life has led to the development of improved alloys (H–8 and H–10).

The other important application is in the manufacture of billet skids, calcinating tubes, kiln nose segments, conveyor rolls and other furnace structural items in the cement, ceramic and steel industries.

H–8

0.4% carbon, 25% chromium, 35% nickel, cast austenitic stainless alloys

Also known generically as type HP40Nb

Description

These steels are an evolutionary development of alloy HK40 (H–7) with the nickel content increased from 20% to 35% and an addition of about 1.5% niobium. They have a high carbon content of more than 0.4% and are generally only available as castings. A typical composition is:

		C	Mn	Si	S	P	Cr	Ni	Nb
Weight %	**Type HP40Nb**	0.45	2	1	<0.01	<0.02	25	35	1.5

These steels are usually purchased as proprietary alloys rather than in accordance with the UNS, ASTM or EN specifications.

UNS/ASTM		EN	Proprietary alloys
N08705	A297 Gr. 'HP40Cb'	1.4857	Doncasters Paralloy H39W Duraloy Thermalloy 64 Manoir Manurite 36X &36XM

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

Background

This alloy was first developed about 40 years ago to provide improvements on alloy HK40, particularly by increased creep performance and resistance to carburisation. These improvements are achieved by increasing the nickel content and by adding niobium to provide a network of stable carbides. Developments have continued and, in recent years, further improvements have been made by the use of microalloying elements such as titanium and zirconium, which form secondary networks of fine carbides. Some grades are supplied with a lower carbon content of about 0.15%, which results in better resistance to thermal shock but at the expense of high-temperature creep rupture strength.

Performance

Alloy HP40Nb is designed to operate for continuous long periods at temperatures up to about 1100 °C and to provide benefits over HK40, which justify the additional cost. Resistance to oxidation is improved and resistance to carburisation is twice that of HK40. At temperatures of about 1100 °C only a modest gain in 100 000-hour rupture life is achieved, but at 1000 °C this alloy provides a 50% improvement, with the microalloyed versions giving a further 5–10%.

At all but the highest temperatures, the lower carbon (0.15%) version offers significant improvements over HK40 with the added benefit of much better resistance to thermal shock. These high-carbon cast alloys do not have good room temperature ductility but HP40Nb is reasonably resistant to sigma formation. However, after long periods of high-temperature service, further deterioration of ductility takes place as carbides grow. While the steel is readily weldable in its original condition, special precautions have to be taken when welding service-aged material.

Applications

These alloys are used almost exclusively in the manufacture of catalytic steam reformer coils and pyrolysis coils for ethylene cracking. The key components in hydrogen, ammonia and methanol plants are the primary reformer furnaces which operate at high pressures in the temperature range 750–1050 °C. The use of HP40Nb allows the tube wall thickness to be reduced, with a consequent increase in catalyst capacity and improvements in heat transfer.

In ethylene production, hydrocarbon feeds (ethane, propane, naphtha, etc.) are thermally cracked in the presence of steam at low pressures and at temperatures up to about 900 °C. HP40Nb's good resistance to carburisation from the hydrocarbon feedstock is a key benefit for this application.

H–9

0.5% carbon, 25–28% chromium, 35–50% nickel, 0–15% cobalt, 5% tungsten, cast austenitic alloys

Also known generically as alloy 22H and Supertherm

Description

These are a pair of related proprietary alloys based on the 25% chromium, 35% nickel system and designed for use in the most aggressive high-temperature environments. Cobalt and tungsten are used in significant quantities, albeit at a cost penalty, to maintain matrix strength at temperatures where carbides begin to dissolve. The carbon content is held at the high level of 0.5% and for this reason these alloys are only available as castings. Higher-silicon versions (~2%) are sometimes produced to improve castability and oxidation resistance. Typical compositions are:

		C	Mn	Si	S	P	Cr	Ni	Co	W	Fe
Weight %	**Alloy 22H**	0.5	0.6	1	<0.01	<0.02	28	50	–	5	15
	Supertherm	0.5	0.6	1	<0.01	<0.02	25	35	15	5	20

The alloys are produced as castings from one of the following proprietary brands:

Alloy 22H	EN	Proprietary alloys
	2.8479	Doncasters Paralloy H48T
		Duraloy 22H & Super 22H (22H + 3%Co)
		Schmidt & Clements Centralloy 8479
		Manoir Manaurite 50W
Supertherm		Duraloy Supertherm
		Schmidt & Clements ET35Co
		Manoir Manaurite 35K

These alloys are always solution treated followed by rapid quenching to give a complex structure with austenite and networks of eutectic carbides.

Background

These alloys were developed in the USA in the 1950s, with the intention of producing alloys superior to anything then available for operation at temperatures up to as high as 1250 °C. Supertherm was a trade name of the Abex Corporation and 22H was designed by the Blaw Knox Corporation.

Performance

Supertherm and 22H provide excellent combinations of very high-temperature creep strength, oxidation and carburisation resistance. Alloy 22H with its higher chromium content provides useful resistance to sulphidation under high-temperature oxidising conditions. While the long-term rupture strengths are not quite as high as for the most modern microalloyed 35/45 types (H–10), they offer unrivalled resistance to hot abrasion without the high cost penalty of cobalt-based superalloys (Stellites). They also have good dimensional stability and high resistance to thermal shock.

Applications

These cast alloys are used primarily in furnaces, kilns and equipment operating at temperatures in the range 950–1250 °C, where a variety of atmospheres may be present and hot abrasive wear is a problem. Typical applications are highly stressed furnace parts, sintering and calcining muffle furnaces, radiant tubes and pyrolysis coils used in the metallurgical ore processing, cement and ceramic industries. Cast parts are often incorporated in areas subjected to hot abrasive products such as cement clinker.

H–10

0.4% carbon, 35% chromium, 45% nickel, cast austenitic alloys

Also known generically as type 35/45

Description

This alloy is a further evolutionary development of alloy HK40 (H–7) with the chromium content increased from 25% to 35% and the nickel content from 20% to 45%, plus an addition of about 1.5% niobium and some micro-alloying. It has a high carbon content of more than 0.4% and is generally only available as castings. A typical composition is:

		C	Mn	Si	S	P	Cr	Ni	Nb
Weight %	**Type 35/45**	0.45	2	1	<0.01	<0.02	35	45	1.5

This is a comparatively new alloy that has not yet been incorporated into national codes or standards. There are, however, a number of proprietary producers and some of these are listed:

Proprietary alloys
Doncasters Paralloy H46M
Duraloy Thermalloy 80
Manoir Manaurite XT & XTM

This alloy is always solution treated followed by quenching to give a complex austenitic structure with eutectic and secondary carbides.

Background

This alloy was first developed about 1990 to provide further improvements on alloy HP40Nb (H–8), particularly in increased high-temperature creep performance and resistance to oxidation and carburisation. These are achieved by increasing both the chromium and nickel contents. Most suppliers offer alloys microalloyed versions containing titanium and zirconium, which form secondary networks of fine carbides. Some grades are supplied with small REM additions (e.g. cerium), which it is claimed help stabilise the surface oxide film and further reduce oxidation and carburisation.

Performance

Alloy 35/45 is designed to operate for continuous long periods at temperatures up to about 1150 °C, which is about the practical upper limit for most of the heat-resistant alloys that can be reasonably easily fabricated. It is also intended to provide benefits over HP40Nb that justify the additional cost. Resistance to oxidation is improved and resistance to carburisation is about 50% better than that of HP40Nb. At temperatures below about 1000 °C this alloy offers no real improvement in 100 000-hour rupture life, but at 1100 °C an improvement of about 30% in rupture stress can be expected.

Applications

This alloy is used almost exclusively in the manufacture of coils for ethylene cracking, in which hydrocarbon feeds (ethane, propane, naphtha, etc.) are thermally cracked in the presence of steam at low pressures and at temperatures up to about 900 °C. However, the radiant sections of some modern cracking furnaces operate at 'end-of-run' tube metal temperatures of up to 1150 °C. The good resistance to carburisation from the hydrocarbon feedstock is also a key incentive for the use of alloy 35/45 in this application.

H–11

50% chromium, 50% nickel, 2% niobium, cast austenitic alloy

Also known generically as alloy IN-657

Description

This is a special high-temperature alloy developed for a specific application and represents the ultimate in this type of alloy composition in that it consists entirely of approximately equal quantities of chromium and nickel with a relatively small addition of either niobium or titanium. The alloy is sometimes described as 50Ni–50Cr–Nb, even though this composition would technically exceed 100%!

The most common form of the alloy is as castings with niobium, designated IN-657, but a wrought version with titanium in place of the niobium is available as IN-671. A typical composition is:

		C	Mn	Si	S	P	Cr	Ni	Nb
Weight %	**IN-657**	0.07	0.5	1	<0.01	<0.02	50	47	1.8

This alloy is generally supplied to one of the following specifications or as proprietary brands;

ASTM	EN	Proprietary alloys
Gr. 50Cr–50Ni-Cb	2.4678	Inco IN-657 & IN-671
	2.4813	Doncasters Paralloy N50W
	2.4680	Duraloy 50/50Cb

The alloy is always solution treated followed by quenching to give an austenitic structure with some carbides.

Background

This alloy was first developed about 1970 by Inco in the UK to provide an alloy that would resist fuel ash corrosion at high temperatures. The alloy was patented and licensed to foundries worldwide. Since the expiration of the patent a number of foundries have introduced their own versions of the alloy. The overall design philosophy was to increase both chromium and nickel to the highest possible levels and so provide maximum resistance to oxidation and carburisation in a wide range of environments.

Performance

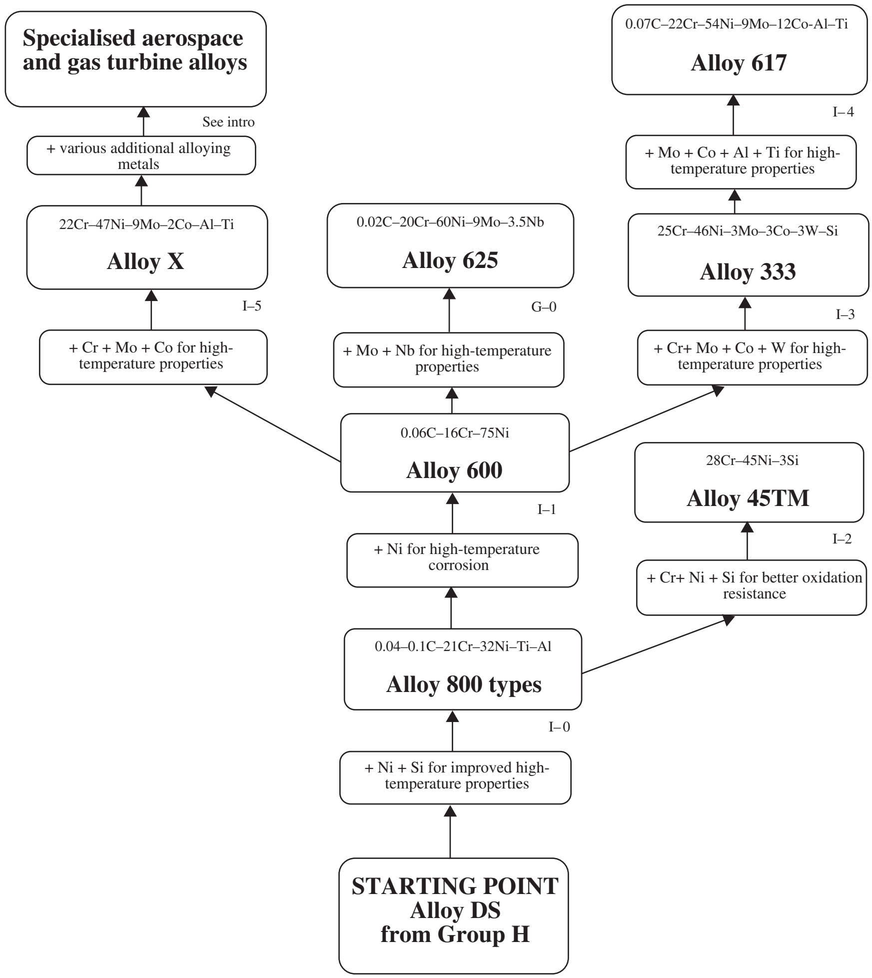
Alloy IN-657 is designed to operate for continuous long periods at temperatures in the range 650–950 °C, and be resistant to hot corrosion by fuel ash containing vanadium pentoxide and alkali metal sulphates arising from the combustion of low-grade heavy fuel oils. The melting point of such compounds can be as low as 630 °C and corrosion of less highly alloyed materials can be rapid and catastrophic. It is not a particularly strong alloy with a fairly low carbon content and only limited strengthening results from the chromium and niobium contents.

Applications

This alloy is the only one that can be used for hangers, tubesheets and tube supports in oil-fired furnaces and boilers where the fuel is dirty, heavy low-grade fuel oil. Typical applications are ships, power stations, oil refineries and petrochemical plants. However, such fuels are not used in reformers and ethylene furnaces because of the catastrophic corrosion that would occur at their high operating temperatures. The use of this high-cost alloy for all the high-temperature components in these furnaces would not be efficient, practicable or cost effective.

Group I

Heat-resistant nickel alloys



Group I: Heat-resistant nickel alloys.

Introduction

Group I starts with alloy DS from Group H, and like Group H is a rather complex group with several branches and sub-branches. These reflect a number of different design philosophies adopted to achieve specific high-temperature properties for particular applications. The main branch shows the evolution of relatively simple nickel alloys leading up to alloy 625, which is widely used not only for its high-temperature properties, but also for its corrosion resistance in aqueous media. For this reason it is included in both Groups G and I.

The two other branches show the development of more complex alloys for general engineering applications and the link with advanced superalloys widely used by the aerospace industry which are outside the scope of this book. One sub-branch illustrates the use of silicon in nickel alloys to improve oxidation and scaling resistance in certain high-temperature gaseous environments.

I–O

Controlled carbon, 21% chromium, 32% nickel, with aluminium and titanium, iron-base alloy

Also known generically as alloy 800, 800H and 800HT

Description

These are iron–nickel–chromium alloys with a similar overall alloy content to type 330, but with a lower chromium: nickel ratio. All three versions have carbon less than 0.1% with controlled levels of aluminium and titanium. Alloys 800H and 800HT both have more tightly controlled carbon and the HT version additionally has higher controlled levels of both aluminium and titanium to ensure minimum high-temperature properties. Typical compositions are:

		C	Mn	Si	S	P	Cr	Ni	Al	Ti
Weight %	**Alloy 800**	<0.1	1	0.5	<0.01	<0.02	21	32	0.2	0.2
	Alloy 800H	0.07	1	0.5	<0.01	<0.02	21	32	0.2	0.2
	Alloy 800HT	0.08	1	0.5	<0.01	<0.02	21	32	0.5	0.5

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

	UNS/ASTM	EN	Proprietary alloys
Alloy 800	N08800	1.4850	Special Metals Incoloy 800, 800H, 800HT.
Alloy 800H	N08810	1.4859	Sandvik Sanicro 31.
Alloy 800HT	N08811	1.4876	VDM Nicrofer 3220.

There are a number of cast versions of alloy 800, including: Doncasters Paralloy CR32W, Manoir Manaurite 900 and Lloyds Thermalloy T52. They are always solution treated followed by quenching to give a stable austenitic structure. They also contain titanium nitrides, titanium carbides and chromium carbides. The heat treatment of the different grades differs somewhat.

Background

Inco first developed alloy 800 in the 1950s as both a corrosion- and heat-resisting alloy with a relatively low nickel content, because at the time nickel was designated a ‘strategic’ metal. Over the following years, the importance of controlling carbon to enhance high-temperature properties was recognised and the alloy 800H version evolved. Subsequently the need to also control both titanium and aluminium within tight limits, together with minimum grain size limits, led to the introduction of alloy 800HT.

Performance

Alloy 800 was developed primarily as an economic high-temperature material, and the subsequent evolution of the 800H and 800HT versions was aimed at improving the maximum allowable design stresses and increasing the operating temperatures. Alloy 800 offers resistance to oxidation, carburisation and sulphidation along with rupture and creep strength and long-term stability at temperatures up to about 800 °C. For applications requiring additional creep properties at higher temperatures, alloys 800H and 800HT are preferred, having higher allowable design stresses. General aqueous corrosion resistance is good, and the reasonably high nickel content provides good resistance to SCC. However, for aggressive environments, more modern, specially designed alloys would normally be used.

Applications

These alloys are used for the fabrication of muffles and radiant tubes, heat treatment trays and baskets in furnace and heat treatment industries. They are also widely used in the petrochemical industry for reformer furnace outlet manifolds and ethylene plant transfer lines, where their resistance to thermal shock during quenching can be beneficial.

Alloy 800HT is also used for superheater and reheater tubing in fossil-fuelled power plants, and for steam generator tubing in nuclear plants. However, the water quality has to be good or there is a risk of pitting attack. In certain locations, alloy 800 has proved to be unsuitable.

I–1

75% nickel, 16% chromium, 8% iron, nickel alloy

Also known generically as alloy 600

Description

This is a simple alloy in terms of alloying additions with a much higher nickel and higher carbon content than alloy DS and with a corresponding cost premium. A typical composition is:

		C	Mn	Si	S	P	Cr	Ni	Fe
Weight %	**Alloy 600**	0.06	0.5	0.3	<0.01	<0.01	16	75	8

The 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
N06600	2.4816	Special Metals Inconel 600
A494 CY40 (cast)		VDM Nicrofer 7216 & 7216H
		Carpenter Pyromet 600
		Rolled Alloys RA600

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

Background

Alloy 600 was originally developed as a high-temperature alloy where the addition of about 15% chromium to the nickel matrix provides good thermal properties well into the oxidising range. It was found to have particularly good corrosion resistance in mineral acids and some pitting environments.

Performance

The alloy microstructure is extremely stable and resistant to long-term ageing and degradation of mechanical properties, particularly toughness and ductility. It is also resistant to nitriding and carburisation.

It has very modest corrosion resistance to mineral acids and the absence of molybdenum severely limits its pitting resistance in aqueous chloride environments. However, alloy 600 has excellent resistance to organic fatty acids and to a range of caustic and alkali chemicals. One of the particular features of this alloy is its resistance to corrosion in certain environments, particularly dry chlorine at temperatures up to about 550 °C.

Applications

This alloy has a wide range of applications in the chemical, petrochemical, food processing and nuclear industries. It is used in the manufacture of heat treatment equipment, high-temperature ducting and muffle furnaces where the combination of carburisation, nitriding and oxidisation resistance combined with long-term thermal stability makes it a very popular alloy choice.

Its resistance to dry halogens at high temperature is exploited in chemical process plant used in the manufacture of vinyl chloride monomer, which is the starting point for the ubiquitous plastic PVC. It is used in specialist high-temperature plant to produce uranium hexafluoride as an essential starting point for enriched nuclear fuels. It also finds widespread application in the production and handling of caustic and alkali solutions and chemicals.

Alongside alloys 400 (J–1) and 800 (I–0), it is one of the nickel alloys used for cooling water heat exchanger and steam generator tubing in water-cooled nuclear power plants. Experience in the clean, demineralised water systems associated with steam generators has generally been very good, but in the latest plants it is being replaced by alloy 690 (G–7). In primary cooling systems using lake water, the corrosion resistance has been variable and alloy 600 has been found to be susceptible to pitting attack.

I–2

28% chromium, 45% nickel, 23% iron, 3% silicon with REM additions, nickel alloy

Also known generically as alloy 45TM

Description

This is quite a complex alloy with about 30% chromium for oxidation resistance and strength and a medium carbon content of about 0.1%. It also contains silicon at 3% and 0.1% REM additions of which about half is typically cerium. A typical composition is:

		C	Mn	Si	S	P	Cr	Ni	Fe	REM
Weight %	**Alloy 45TM**	0.1	0.6	3	<0.01	<0.02	28	45	23	0.1

The alloy is produced as a range of wrought products and is supplied in accordance with one of the following specifications:

UNS/ASTM	EN	Proprietary alloy
N06045	2.4889	VDM Nicrofer 45TM

This alloy is always solution treated followed by rapid quenching to give a stable austenitic microstructure.

Background

Alloy 45TM is a modern high-temperature alloy developed about 1980, which exploits the synergistic effects of silicon and REMs in providing a very stable oxide layer that is adjacent to and just below the chromium oxide film. This silicon oxide layer prevents growth of the primary chromium oxide layer and therefore reduces the risk of spalling and continuous degradation.

Performance

This alloy has excellent oxidation resistance up to about 1000 °C and is the optimum choice for combined chlorination/oxidation/sulphidation and carburisation resistance. The combined oxide layers are virtually immune to all these forms of attack, either singly or in combination. The resistance is also maintained under cyclic conditions.

The alloy has reasonable high-temperature and creep properties but is inferior to most other high-temperature alloys such as alloys 600 (I–1), 625 (G–0) and 617 (I–4).

Applications

This alloy is used solely as a high-temperature alloy where its resistance to a wide range of gaseous environments can be exploited. The most widespread uses are in the manufacture of high-temperature components for coal gasification plants and waste incineration plants. In both cases the fuels being processed may be of uncertain and varied origin and it is important to use a material that will be as resistant as possible to any high-temperature combustion products that might arise.

Other applications include furnace components and industrial heat exchangers handling a range of flue gases. It is sometimes offered as material for critical components in catalytic crackers where the extended life justifies the additional costs.

The alloy has also been used to handle gaseous hydrofluoric acid as a process step in the production of uranium hexafluoride for nuclear fuel enrichment.

I–3

25% chromium, 46% nickel, 3% molybdenum, 3% cobalt, 3% tungsten, nickel alloy with 1% silicon

Also known generically as alloy 333

Description

This is a complex alloy with about 25% chromium for oxidation resistance, molybdenum, cobalt and tungsten for solid solution and carbide strengthening and silicon for improved high temperature scaling resistance. It also has a fairly low carbon content of about 0.05%. Compared with many nickel-base alloys, it contains a relatively high iron content of about 18%, and this offers some cost savings. A typical composition is:

		C	Mn	Si	S	P	Cr	Ni	Mo	Fe	Co	W
Weight %	Alloy 333	0.05	0.6	1.2	<0.01	<0.01	25	46	3	18	3	3

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	Proprietary alloy
N06333	Rolled Alloys RA333

The alloy is always solution treated followed by rapid quenching to give a stable austenitic microstructure with some complex carbides.

Background

Alloy 333 was developed in the USA about 1950, primarily as an economic high-temperature alloy with exceptionally good scaling resistance. The name derives from the 3% additions of the three main solid solution alloying elements, namely molybdenum, cobalt and tungsten, hence the designation 333.

Performance

This alloy provides good high-temperature strength and oxidation resistance at temperatures above 1000 °C and has creep rupture properties at this temperature that are comparable with higher nickel-containing alloys such as alloy 600 (I–1). The addition of over 1% silicon improves oxide stability and reduces high-temperature spalling of the oxide film. The alloy is resistant to high-temperature sulphidation, carburisation and oxidation, as well as metal dusting. It is also resistant to sulphuric acid attack and to chloride and polythionic acid SCC, particularly when these form below the dew point under shutdown conditions. Alloy 333 has an excellent ability to withstand repeated thermal shock caused by oil or water quenching.

Applications

This alloy is used primarily as a high-temperature alloy in diverse chemical and petrochemical plant applications. Particular examples are radiant tubes, tube hangers for petroleum refinery and power boilers and heat treatment fixtures and fittings. It is also used for refinery flare tips, especially those burning a wide range of waste products.

Alloy 333 has exceptional resistance to erosion by molten glass and has replaced platinum spinnerets in the manufacture of fibreglass.

I–4

22% chromium, 54% nickel, 9% molybdenum, 12% cobalt, plus aluminium, nickel alloy

Also known generically as alloy 617

Description

This alloy has a composition quite closely related to alloy 625 except that a proportion of the nickel is replaced by about 12% cobalt and the niobium has been eliminated. There is an addition of about 1% aluminium plus some titanium. The alloy was primarily designed for high-temperature applications and the carbon level is controlled at about 0.1%, but it also offers useful corrosion resistance. A typical composition is:

		C	Mn	Si	S	P	Cr	Ni	Mo	Co	Al	Ti
Weight %	Alloy 617	0.1	0.5	0.5	<0.01	<0.01	22	54	9	12	1.2	0.3

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

UNS/ASTM	EN	Proprietary alloys
N06617	2.4663	Special Metals Inconel 617 VDM Nicrofer 5520Co

This alloy is always solution treated followed by rapid quenching to give a stable, precipitation-hardened austenitic microstructure.

Background

This alloy is quite new and was developed towards the end of the 20th century as an improvement on alloy 625 for high-temperature applications. In particular, it was designed to have better long-term high-temperature stability. With a high chromium and molybdenum content it also combines good corrosion resistance with the high-temperature properties. However, the very high cost of cobalt makes this alloy relatively expensive and it tends to be used only where this cost can be justified.

Performance

Alloy 617 has similar ambient and elevated temperature tensile properties to alloy 625, but at the highest service temperatures, above about 900 °C, it offers significantly better creep rupture strength and ductility combined with better long-term stability. It also has excellent resistance to oxidation and carburisation.

The combination of chromium and molybdenum ensures that the alloy has very useful general, pitting and SCC resistance. While this is not as good as some very low-carbon superaustenitic stainless steels and nickel alloys, specifically designed for the most aggressive conditions, it does provide benefits in certain environments.

Applications

This alloy is being increasingly used by the chemical and petrochemical industries in combustion and pyrolysis furnaces where, as a wrought material that can be supplied as small diameter tube, it is a viable alternative to some of the high-carbon austenitic alloys only available as castings. It is also used as high-temperature ducting, turbine components and casings, particularly in modern high-performance combined cycle gas-fired power stations.

The combination of high-temperature and corrosion-resistant properties can be used to good effect in those high-temperature components that are also exposed to corrosive conditions such as salt spray. An example of this would be waste gas flare tips on offshore oil and gas platforms.

This alloy, in the form of welding consumables, is used to weld a wide range of heat-resisting alloys, both similar and dissimilar joints, particularly where matching consumables are not readily available.

I–5

22% chromium, 47% nickel, 9% molybdenum, 2% cobalt with tungsten, aluminium and titanium, nickel alloy

Also known generically as alloy X

Description

This is a complex alloy with about 20% chromium for oxidation resistance, molybdenum, cobalt and tungsten for solid solution strengthening and aluminium and titanium for intermetallic precipitation hardening. It also has a moderate carbon content of about 0.15%. Compared with many nickel alloys, it contains a relatively high iron content of about 18%, and this offers some cost savings. Typical composition:

		C	Mn	Si	S	P	Cr	Ni	Mo	Fe	Co	W
Weight %	**Alloy X**	0.15	0.6	0.5	<0.01	<0.01	22	47	9	17	2	0.7
		Plus **0.2 Al** and 0.15 Ti										

The 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
N06002	–	Special Metals INCO HX (formerly NIMONIC PE13)
A567 Gr. 5 (cast)	2.4665	Haynes Hastelloy Alloy X

This alloy is always solution treated followed by rapid quenching to give a stable austenitic structure with some carbides and intermetallics.

Background

This alloy can be described as the first of a series of nickel–chromium–iron ‘superalloys’, developed at the end of World War II to meet the needs of a rapidly developing jet aero engine industry. It is based on the 80% Ni, 20% Cr alloy originally produced at the end of the 19th century as electrical resistance heating element wire. In broad terms, alloying additions of molybdenum, cobalt and tungsten provide solid solution strengthening while the aluminium and titanium provide precipitation hardening by forming intermetallic compounds such as gamma prime. From alloys such as alloy X, a whole family of nickel- and cobalt-based superalloys has been developed for high-temperature gas turbine and aero engine applications, but these fall outside the scope of this guide.

Performance

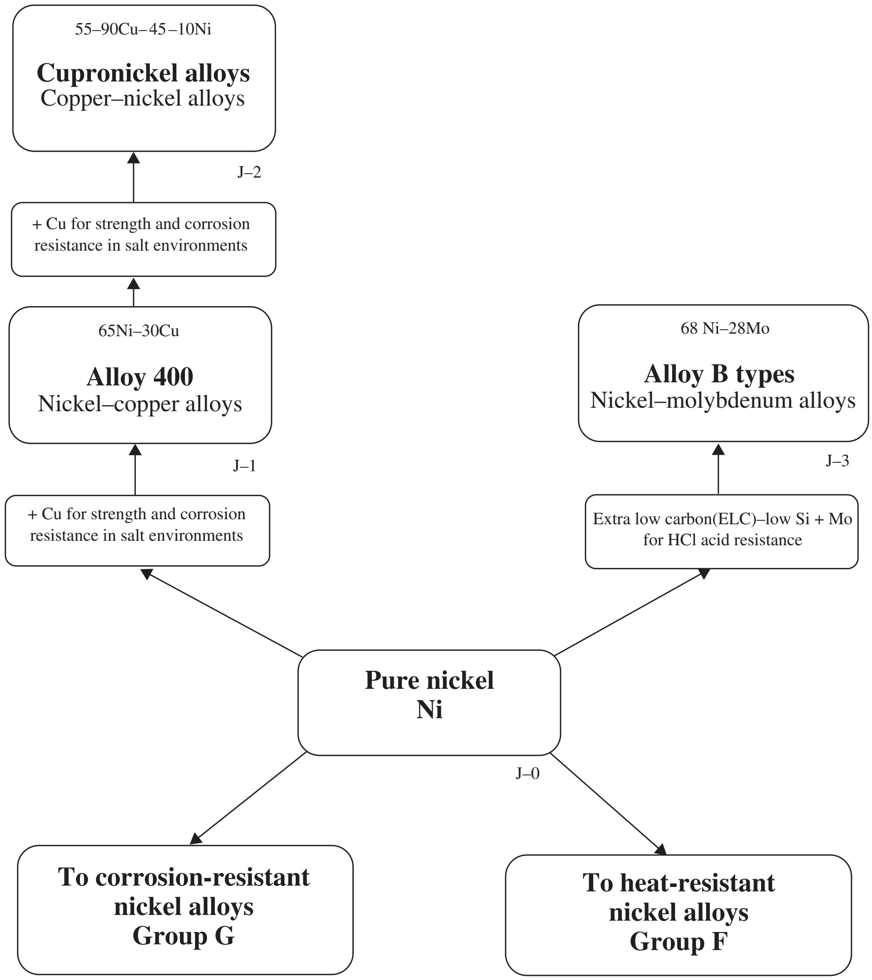
This alloy provides good high-temperature strength and oxidation resistance at high temperatures up to about 1200 °C. It performs well in a range of both oxidising and reducing conditions and resists carburisation and nitriding in a wide range of environments. Compared with some other complex superalloys, particularly those with higher titanium and aluminium additions, it is relatively easy to weld and fabricate.

Applications

This alloy is used primarily as a high-temperature alloy, but more modern alloys have largely overtaken its major role in critical aero engine and gas turbine components. However, it is still quite widely used in high-temperature furnace parts, particularly when there is exposure to a range of atmospheres such as those found in some multi-fuel furnaces and waste incineration plants. It is still used in some chemical and petrochemical plants, which can benefit from its high resistance to SCC in a wide range of media, but alloy 625 (G–0), is a more competitive and versatile alloy for many applications.

Group J

Nickel, nickel–copper and nickel–molybdenum alloys



Group J: Nickel, nickel–copper and nickel–molybdenum alloys.

Introduction

Group J represents the pinnacle of the alloy tree, in the sense that at the base of the tree is plain carbon steel and the top is pure nickel. While pure nickel has a number of useful applications in its own right and these are described in the relevant data sheet, its position at the top the tree is intended to show the two key links back to Group G corrosion-resistant nickel alloys and Group I heat-resistant nickel alloys.

Also included are two groups of corrosion-resistant alloys that contain essentially nickel and one other element. The first of these is the nickel–copper system, which extends from the nickel-rich Monel type alloys through to the copper-rich cupronickels. The second is a group of specialised alloys that contain only nickel and high levels of molybdenum.

J–0

Pure nickel

Also known generically as alloy 200 and alloy 201

Description

Alloy 200 is commercially pure wrought nickel (99.5%) with a carbon content of about 0.1%. All other elements such as iron, copper and manganese are controlled and are present only as residuals. Alloy 201 is the low-carbon version of alloy 200, with a maximum carbon content of 0.02%. A small amount of cobalt as a residual from the nickel refining process is usually included in the value for the nickel content. Typical compositions are:

		Ni	Cu	Fe	Mn	Si	S	C
Weight %	**Alloy 200**	>99	<0.25	<0.40	<0.35	<0.35	<0.01	<0.15
	Alloy 201	>99	<0.25	<0.40	<0.35	<0.35	<0.01	<0.02

These alloys are normally supplied in accordance within one of the following specifications:

	UNS	EN	Proprietary alloys
Alloy 200	N02200	2.4066	Special Metals Nickel 200
		2.4060	VDM Nickel 99.6
Alloy 201	N02201	2.4061	Special Metals Nickel 201
		2.4068	VDM Nickel 99.2

The alloys are usually supplied in the annealed condition to give a virtually pure nickel austenite microstructure.

Background

These are essentially pure metals with negligible alloying. They represent one end of the iron–nickel spectrum of stainless steels and nickel alloys. However, they have useful properties and are important materials in their own right.

Performance

Pure nickel is resistant to various reducing chemicals and has unexcelled resistance to caustic alkalies. While nickel resists attack from many common acids, both inorganic and organic, in their pure condition, most practical applications involve some contamination and this leads to rapid attack. However the outstanding characteristic of nickel is its resistance to caustic soda and most other alkalis. In caustic soda, the alloys have excellent resistance at all concentrations and temperatures including the molten state. Resistance to attack is provided by a black nickel oxide protective film.

Pure nickel is a low-strength but highly ductile material in the annealed condition. Strength can be increased by work hardening and some product forms are supplied in the 'hard' condition.

Alloy 200 suffers from carbon precipitation or graphitisation after prolonged periods at high temperature and its use should be restricted to temperatures below about 300 °C. Alloy 201, with a very low carbon content, does not suffer from this effect and can be used at temperatures up to about 650 °C.

Compared with other nickel-base alloys, pure nickel has good thermal and electrical conductivity. It also has a high Curie temperature and good magnetorestrictive properties.

Applications

The corrosion resistance of pure nickel makes it particularly useful for maintaining product purity in the manufacture and handling of foods, synthetic fibres and caustic alkalis. It is also used in general structural applications where resistance to corrosion is a prime consideration. Other applications include chemical transportation drums, electrical and electronic parts, aerospace and missile components.

Alloy 201 tends to be used for the higher-temperature applications and these include caustic evaporators, combustion boats, plater bars and electronic components.

J–1

65% nickel, 30% copper alloy

Also known generically as alloy 400

Description

Alloy 400 is a nickel-base alloy with about 30% of copper to give a solid-solution alloy that can be hardened only by cold working. There is no other deliberate alloying and carbon, manganese, silicon and iron contents are all controlled below maximum limits. A typical composition is:

		Ni	Cu	Fe	Mn	Si	S	C
Weight %	**Alloy 400**	>63	30	<2.5	<2.0	<0.5	<0.02	<0.3

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

UNS	EN	Proprietary alloys
N04400	2.4360	Special Metals Monel 400
	2.4361	VDM Nicorros

This alloy is usually supplied in the annealed condition to give a single-phase binary alloy structure.

Background

Nickel and copper are mutually soluble in all proportions and form a continuum of alloys from pure nickel through to pure copper. In practice, most commercial alloys are based on 65% nickel and 30% copper, sometimes loosely described as 'Monel' and a series of alloys with copper ranging from 70 to 90% and nickel from 30 to 10% which are usually described as cupronickels (J–2).

Performance

This alloy exhibits resistance to corrosion by many reducing media. It is also generally more resistant to attack by oxidising media than the higher copper cupronickels. It also resists seawater corrosion, but in stagnant conditions it can be susceptible to both pitting and crevice corrosion. It is probably the most resistant of all alloys to attack by hydrofluoric acid in all concentrations up to the boiling point and it is suitable for use with both sulphuric and hydrochloric acids under reducing conditions.

Alloy 400 does not offer particularly high strength and for applications such as pumps and valves where higher strengths are required a modified alloy, K-500, is available. This is similar in composition to alloy 400 but has an addition of about 2.5% aluminium and 0.5% titanium to provide some precipitation hardening. This effectively doubles the tensile strength to more than 1000 MPa.

Applications

Alloy 400 is widely used, particularly in marine environments and chemical processing. Typical applications are valves and pumps; pump and propeller shafts; marine fittings and fixtures; electrical and electronic components; chemical processing equipment and fuel; and water storage tanks.

It is widely used in oil refineries for critical components in crude oil processing stills, process vessels and piping, and more widely in the power generation and chemical industries for boiler feed water heaters and other heat exchangers and deaerating heaters.

It is an essential material for hydrofluoric acid manufacturing plants and in equipment and vessels handling the acid and its fluorides. A particular example is in nuclear fuel enrichment plants, which produce uranium hexafluoride as an intermediate product in the separation of fissile material.

J–2

Copper with 10–45% nickel alloys

Also known generically as cupronickel alloys

Description

This is a group of alloys often described as cupronickels because copper is the major constituent and nickel the only other major alloying addition. Three alloys are described, with nickel contents ranging from 10 to 45%. One alloy also has small deliberate additions of manganese. Typical compositions are:

		Ni	Cu	Fe	Mn	Si	S	C
Weight %	**Alloy 90/10**	10	89	<0.5	<0.2	<0.5	<0.02	<0.05
	Alloy 75/25	25	74	<0.5	0.3	<0.5	<0.02	<0.05
	Alloy 70/30	30	69	<0.5	<0.2	<0.5	<0.02	<0.05

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

	UNS	EN	Proprietary alloys
Alloy 90/10	C70600	2.0872	IMI Kunifer 10, VDM Cunifer 10
Alloy 70/30	C71500	2.0882/3	IMI Kunifer 30, VDM Cunifer 30

These alloys are usually supplied in the annealed condition to give a single-phase binary alloy structure.

Background

Copper and nickel are mutually soluble in all proportions and form a continuum of alloys from pure nickel through to pure copper. In practice, most commercial cupronickel alloys are based on copper with 10–30% nickel with in some cases minor alloying additions such as manganese. The nickel-rich Alloy 400 is described in J–1.

Performance

The 90/10 and 70/30 alloys have excellent corrosion resistance to seawater and other salt solutions. The 70/30 alloy is the stronger of the two and is superior under impingement and cavitation conditions. Both alloys have good resistance to bio fouling, with the higher copper content of the 90/10 offering some additional benefits.

The alloy with 25% nickel and a small manganese addition offers improved strength and wear resistance.

All the cupronickel alloys retain reasonable high-temperature strength when compared with other copper-based alloys without nickel.

Applications

The most widespread range of applications is in marine and seawater environments. Both 90/10 and 70/30 alloys are used in seawater condensers in desalination plants, as well as pipework and vessels in the manufacture and processing of salt from brine. The good resistance to both corrosion and bio fouling is exploited in the cladding of ship hulls and offshore structures, particularly in the ‘splash zone’.

The alloys are increasingly being used for safety-critical components in road vehicles. Items such as hydraulic brake pipes, suspension and cooling systems can resist salt corrosion and offer better performance than painted or galvanised steel.

The 25% nickel alloy with manganese is a commonly used alloy for the manufacture of coins and medals, where the combination of corrosion and wear resistance ensures a long life.

J–3

Nickel alloys with 28% molybdenum and small additions of iron and chromium

Also known generically as alloy B and variants

Description

These alloys are all based on nickel with a primary addition of about 28% molybdenum. Versions such as B-2, B-3 and B-4 have essentially the same basic composition as alloy B, but with other small alloying additions. However, modern production methods have enabled both the carbon and silicon levels to be controlled to very low levels. Typical compositions are:

		C	Mn	Si	S	P	Cr	Ni	Mo	Fe
Weight %	**Alloy B-2**	<0.01	<1	<0.1	<0.01	<0.02	-	70	28	-
	Alloy B-3	<0.01	<3	<0.1	<0.01	<0.02	1.5	68	28	1.5
	Alloy B-4	<0.01	<1	<0.05	<0.01	<0.02	1	66	29	3.5

The alloys are produced primarily as wrought material and are supplied in accordance with one of the following specifications:

	UNS	EN	Proprietary alloys
Alloy B-2	N10665	2.4617	Haynes Hastelloy B-2 VDM Nimofer 6928
Alloy B-3	N10675	–	Haynes Hastelloy B-3
Alloy B-4	N10629	2.4600	Haynes Hastelloy B-4 VDM Nimofer 6629

These alloys are always solution treated followed by rapid quenching to give a stable fully nickel-base austenitic microstructure.

Background

This alloy was originally developed as a casting alloy (alloy B). Welded fabrications in wrought material were difficult to produce and performed badly because of the relatively high carbon and silicon contents. Improvements in alloy production technology in the 1970s led to the development of the very low-carbon and silicon version, which was designated as alloy

B-2. In the 1990s, further modifications were made, with small additions of chromium and iron to improve resistance to SCC and improve weldability. These alloys are designated B-3 and B-4. Development of this alloy system still continues and a new alloy B-10, with about 6% iron and 8% chromium but reduced molybdenum of about 23% was introduced in 1997 by VDM.

Performance

Alloy B types have excellent resistance to hydrochloric acid at all concentrations and temperatures. They also withstand hydrogen chloride and sulphuric, acetic and phosphoric acids. They have good resistance to all forms of corrosive attack and the low carbon and silicon contents ensure that the weld HAZ is not sensitised; fabrications can usually be used in the as-welded condition.

However, the presence of ferric or cupric salts causes the passive film to break down and therefore contamination from these salts must be avoided. The newer grades, such as B-10, are claimed to be more resistant to this form of contamination.

Applications

These alloys are used by the chemical industry in plant manufacturing and processes using the acids listed above, where the high alloy cost can be justified in terms of plant life and reliability. They are particularly resistant to acetic acid and are used in the production of acetic anhydride, a major starting material for many products. Applications include pumps, valves, process vessels, storage tanks and pipework systems.

Appendix 1: Abbreviations

The following abbreviations are used in this book and are worthy of some explanation:

AISI – American Iron and Steel Institute: A standards organisation.

AOD – argon oxygen decarburisation: A method of producing very low-carbon stainless steels using a mixture of argon and oxygen, and widely introduced about 1970.

ASME – American Society of Mechanical Engineers: A Standards and Code organisation.

ASTM – American Society for Testing and Materials: A standards organisation.

CEGB – Central Electricity Generating Board: A former nationalised organisation responsible for electricity generation in the UK (except Scotland) prior to privatisation.

CTOD – crack tip opening displacement: A measure of material fracture toughness using slow strain rates.

ELC – extra low carbon: Low carbon in stainless steels and nickel alloys is usually taken to be less than 0.03%. Extra low carbon is less than 0.02%, although modern steel and alloy processing technology can give carbon levels of less than 0.01%.

EN – Euro Norm: A system of standards being introduced by the European Union and intended to eventually replace all national standards of the member states.

FGD – flue gas desulphurisation: A process applied mainly to coal-fired power stations, where the combustion products, or flue gases, are cleaned of harmful contaminants, particularly sulphur compounds.

HAZ – heat-affected zone: That region of the parent material adjacent to a weld where the heat of the welding operation changes the microstructure.

LNG – liquefied natural gas: Methane.

LPG – liquefied petroleum gas: Propane, butane, etc.

N + T – normalising and tempering: A heat treatment where low-alloy steels are heated and cooled in air (slower than quenching) to produce some hardening followed by a further heat treatment to improve toughness.

PRE – pitting resistance equivalent: A formula designed to give a measure of the pitting corrosion resistance of an alloy based on the content of those elements that enhance pitting resistance.

PRE – Cr + 3.3Mo is the original formula intended for austenitic stainless steels without nitrogen additions.

PREn – Cr + 3.3Mo + 16N is the formula most widely used for duplex, superduplex and superaustenitic stainless steels. However, some authorities believe that a multiplier of 30 for nitrogen is more appropriate to high-nitrogen superaustenitic stainless steels.

PREw – Cr + 3.3 (Mo + 0.5W) + 16N is the formula used for those superduplex stainless steels that contain tungsten.

Note: There is reasonable agreement that the above formulae are appropriate to stainless steels. However, there is some debate as to whether their use can be extended to much higher alloyed corrosion-resistant nickel-base alloys. Some authorities are using a formula specific to nickel alloys which is:

PREN – Cr + 1.5 (Mo + W + Nb) + 30N – 0.5Cu, which gives values in the range 45 to >50 for the most highly corrosion-resistant nickel alloys.

PVC – polyvinyl chloride: one of the more common synthetic plastics.

PWHT – post-weld heat treatment: A heat treatment carried out on a welded joint after welding is completed, designed to reduce residual stresses and sometimes to temper microstructures in the weld and HAZ.

Q + T – quenched and tempered: A heat treatment whereby alloy steels are cooled rapidly to give a hard microstructure and then heated for a period of time to give controlled softening and improve toughness.

REM – rare earth metals: Elements such as cerium used for inclusion shape control in steel making and improved oxidation resistance in stainless steels.

SCC – stress corrosion cracking: This is a form of cracking caused by simultaneous presence of a tensile stress and a specific corrosive medium. Chloride stress cracking of austenitic stainless steels is probably the best-known example.

UNS – unified numbering system: A system devised to enable more than 4000 alloys and metals to be described by a unique number. More information is given in Appendix 2.

USC – ultra supercritical: A term applied to the most recent designs of thermal power stations where the steam conditions are typically 325 bar at 620 °C.

Appendix 2: Specifications

The specification of alloys is a complex subject but the intention of this short section is to give a brief introduction to the specifications referenced in the data sheets. In general, three different specifications are given, but it should be noted that not all alloys are covered by all three specifications.

Unified Numbering System (UNS)

Unique reference numbers are given in a publication produced jointly by the Society of Automotive Engineers Inc. (SAE) and the American Society for Testing and Materials (ASTM). There are over 4000 designations for metals and metallic alloys and it is a means of correlating many nationally used metal and alloy numbering systems. A UNS designation is not, in itself, a specification since it establishes no requirements for product form, condition, properties or quality.

An outline of the system for those alloys contained within the book is given below.

- C00001 to C99999 Copper and copper alloys.
- J00001 to J99999 Cast steels (except tool steels).
- K00001 to K99999 Miscellaneous steels and ferrous alloys.
- N00001 to N99999 Nickel and nickel alloys.
- S00001 to S99999 Heat- and corrosion-resistant (stainless) steels.

Each alloy therefore has a unique reference number made up from a prefix letter and five digits. In many cases some of the digits are identical to an internationally recognised grade or alloy type. For example:

- Type 316 stainless steel has the UNS number S**316**00.
- Nickel alloy 625 has the UNS number N06**625**.

Other examples will be found in the data sheets.

American Society for Testing and Materials (ASTM)

ASTM specifications are probably the most widely used specifications worldwide. The ASTM is closely linked to the ASME, which in turn has a very strong influence on the international chemical and petrochemical industries.

The ASTM is also a partner in the UNS system and many standards are cross-referenced to the UNS numbers. However, many standards cover product forms, properties, condition, etc. which are not included in the UNS specification. There are many hundreds of these specifications, some of which designate alloys by a grade reference, e.g. 316, and some of which relate to specific product forms, such as plate and sheet or pipe and tube. It not possible to include all the appropriate specifications in the data sheet, but UNS numbers are given and the reader is advised to use this as the entry point into the ASTM system. Most manufacturers reference the appropriate ASTM standards in their material data sheets. For example:

Alloy 625:	Plate and sheet	B443
	Billet and rod/bar	B446
	Seamless pipe and tube	B444
	Welded pipe and tube	B704 & B705
	Fittings	B366.

Euro Norm (EN)

Euro Norm is the European Union's specification system, which was developed in the second half of the 20th century and is intended to replace the national specifications of the member states. There are standards that cover the different alloy types and the quality requirements for the various product forms. A typical specification would be EN 10088-2, which covers stainless steels. Within the specification, each type or grade of steel is given a designation based on composition and an alloy number.

The composition designation applies to alloy steels (except high-speed steels) where the content by weight of at least one alloying element exceeds 5%. For this category, the designation begins with the letter X, followed by a number, which is 100 times the average specified carbon content, followed by chemical symbols representing the alloying elements in decreasing order of quantity. This in turn is followed by a number, which gives the typical content of the element indicated. For example:
EN 10088-2, X2CrNi18-9, has a nominal composition of 0.02%C, 18%Cr and 9%Ni.

These composition codes are not included in the data sheets because more comprehensive compositions are given for each alloy. However, locating the appropriate steel or alloy number can readily identify the code, in the relevant standard, if necessary.

The steel or alloy number is complementary to the designation given above and, like the UNS system, consists of a fixed number of digits, which is more convenient than a name for data processing. The system is similar to the German 'Werkstoff Number' used in the DIN standards. The first number for alloy steels is ‘1.’ followed by two digits, which define the alloy group, followed by two digits, which define the alloy. Nickel alloys are prefixed by the digit 2. For example:

- Alloy 430 would be designated Material No. 1.4016.
- Alloy 617 would be designated Material No. 2.4663.

Appendix 3: Product forms

In order to construct modern industrial process plant, it is necessary to have the most appropriate alloy available in a range of product forms. These include plate and sheet, pipes, which might be welded or seamless, tubes and forgings for flanges, nozzles, bends and other components. Castings are also needed, particularly for pump and valve bodies, impellors, etc. Finally there may be a need for machined components for bolting and fixing, thin strip for sheathing and gaskets and wire rod for drawing to smaller diameters for weaving meshes and for welding consumables. There may be minor variations in composition between different product forms of the same alloy, which reflect differences in process route.

Ideally, any viable alloy should be available in all these product forms if it is to be properly exploited. In fact, the relative commercial success of some alloys in the past has been due as much to their availability as to their technical performance.

Unfortunately, it is not always possible to produce an alloy in all product forms. In particular, some of the more highly alloyed, high-carbon austenitic alloys are designed specifically for very high-temperature strength. This means that they are highly resistant to deformation at the temperatures, which would normally be used for forging and cannot therefore be produced, for example, as plate or wire rod. A number of these alloys are available only as castings, which necessarily limits the product forms and their application. The same is true for many advanced gas turbine alloys, which are only available as castings.

Different product forms are sometimes referred to in specifications and grade designations. The ASTM uses the following abbreviations:

- F – forgings.
- T – tube.
- P – pipe.
- C – castings.

The UNS system usually allocates different numbers for wrought and cast versions of the same alloy.

Appendix 4: Alloying costs

The choice of which alloy to use for a particular application is often decided on economic grounds. In recent years, lifetime costing has become a well-recognised discipline, where maintenance and output losses are balanced against initial capital cost. Safety and environmental factors also have an important impact on alloy choice. Nevertheless, initial alloy cost is still a primary factor.

Some alloying elements are significantly more expensive than others, based mainly on their rarity and costs of extraction, processing and purification. Most modern alloys rely on high-quality raw materials to limit the pick up of residual and tramp elements, which could have an adverse effect on performance.

The relative cost and proportion of an alloying element have a significant bearing on the final alloy cost. For example, nickel is much more expensive than iron, is used in significant quantities in many stainless steels and is the majority element in nickel-based alloys. Cobalt is even more expensive, but used in a relatively small number of alloys and in most cases, in small quantities.

Metal prices change on a daily basis, dependent on supply and demand, strategic importance and even the political climate in the country(s) of origin. For this reason it is impossible to give an accurate table of costs. It is, however, possible to give a guide using iron as the base 1 and roughly comparing the other major alloying elements to this base cost index (Table 1).

Table 1 Approximate cost of major alloying elements relative to iron (cost index 1)

Element	Symbol	Cost index
Iron	Fe	1
Manganese	Mn	4
Chromium	Cr	8
Nickel	Ni	40
Molybdenum	Mo	60
Cobalt	Co	110
Tungsten	W	50
Vanadium	V	70
Niobium	Nb (Cb)	90
Copper	Cu	10

Using a similar system, the relative costs of a number of alloy types are shown in Table 2. It should be noted that these are only indicative values and will vary significantly with individual grade and product form.

Table 2 Approximate cost of some alloy types relative to plain carbon steel (cost index 1)

Alloy type	Cost index
Mild steel	1
Austenitic stainless steel – 304L	3
Superaustenitic stainless steel	6
Nickel alloy – 625	15

Appendix 5: The role of individual elements

It is quite remarkable that only sixteen, plus a few rare earth elements, of the hundred or so elements in the periodic table can be combined in many subtle ways to produce the alloys described in this book. A glance at the periodic table (Table 3) shows that these elements fall into two main groups. The light non-metallics (B, C and N) and semi-metallic elements (Al and Si) are in periods 2 and 3 of the table. The remaining heavier alloying metallics are all close together in periods 4, 5 and 6.

This book is not intended to be a metallurgical textbook, but it is believed that the non-specialist reader will find that a brief introduction to the role of the various elements is beneficial to a better understanding of the properties and applications of the alloys dealt with in the book. The elements are described in order of atomic number, and not in any particular order of importance.

Boron (5) is added as a few parts per million to some of the latest low-alloy and creep-resisting steels. It increases the hardenability of the microstructure and forms boron nitrides and boron carbo-nitrides, which improve creep strength. It is also used to increase neutron absorption in some stainless steels used for the transportation and storage of nuclear materials.

Carbon (6) is the most potent hardening and strengthening element in carbon, carbon–manganese and low-alloy steels.

In all the alloys described in this book, carbon is either controlled to careful limits or is kept as low as possible. In broad terms, the controlled carbon versions are used for high-temperature applications whereas the very low-carbon alloys tend be used for aqueous corrosion resistance. The role of carbon in the high-temperature alloys is primarily to form carbides with strong carbide formers such as Mo, W, V and Nb, which help pin grain boundaries and so improve creep strength.

Nitrogen (7) is kept as low as possible in many steels and alloys. However, in some of the newer low-alloy creep-resisting steels, small additions are made to form stable nitrides, which, like stable carbides, can improve creep performance at higher temperatures.

Nitrogen is now a very important alloying element in many stainless steels, particularly duplex, superduplex and superaustenitic types. It is a strong austenite stabiliser and increases strength and improves pitting and crevice corrosion resistance.

Table 3 The periodic table of elements: those elements described in this appendix are highlighted

Group Period	1	2	*	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1																		2
	H																		He
2	3	4												**5**	**6**	**7**	**8**	9	10
	Li	Be												**B**	**C**	**N**	**O**	F	Ne
3	11	12												**13**	**14**	**15**	**16**	17	18
	Na	Mg												**Al**	**Si**	**P**	**S**	Cl	Ar
4	19	20		21	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	30	31	32	33	34	35	36
	K	Ca		Sc	**Ti**	**V**	**Cr**	**Mn**	**Fe**	**Co**	**Ni**	**Cu**	Zn	Ga	Ge	As	Se	Br	Kr
5	37	38		39	40	**41**	**42**	43	44	45	46	47	48	49	50	51	52	53	54
	Rb	Sr		Y	Zr	**Nb**	**Mo**	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
6	55	56	*	71	72	73	**74**	75	76	77	78	79	80	81	82	83	84	85	86
	Cs	Ba		Lu	Hf	Ta	**W**	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
7	87	88	**	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118
	Fr	Ra		Lr	Rf	Db	Sg	Bh	Hs	Mt	Ds	Uuu	Uub	Uut	Uuq	Uup	Uuh	Uus	Uuo
*Lanthanides			*	**57**	**58**	**59**	**60**	**61**	**62**	**63**	**64**	**65**	**66**	**67**	**68**	**69**	**70**		
				La	**Ce**	**Pr**	**Nd**	**Pm**	**Sm**	**Eu**	**Gd**	**Tb**	**Dy**	**Ho**	**Er**	**Tm**	**Yb**		
**Actinides			**	89	90	91	92	93	94	95	96	97	98	99	100	101	102		
				Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No		

Aluminium (13) is a strong deoxidiser, nitride former and grain refiner. At fairly high levels it can improve oxidation resistance by helping to stabilise the oxide film. In nickel-base alloys, in conjunction with titanium, it promotes age-hardening and is used both in some high- and low-temperature alloys.

Silicon (14) is present in many alloys only as a minor residual from deoxidation, but is a strengthening element in its own right. In some of the complex nickel-base alloys it is kept as low as possible to avoid the formation of detrimental intermetallics. However, in combination with chromium it helps to stabilise the oxide film and prevent high-temperature spalling. It is therefore used in some high-temperature austenitic stainless steels and nickel alloys. Silicon improves the fluidity of many alloys and some castings do have somewhat higher levels than the wrought versions.

Titanium (22) is used to stabilise stainless steels such type 321 (E–0). It combines with excess carbon and so reduces the risk of intergranular corrosion. In nickel-base alloys it is used in conjunction with aluminium to promote age hardening.

Vanadium (23) is used in many low-alloy and creep-resisting steels to promote fine grain size, to precipitation harden the matrix and to form stable carbides and nitrides which promote good high-temperature creep properties.

Chromium (24) is the element that is responsible for the basic stainlessness of iron-based alloys. It promotes the formation of a stable oxide film and therefore enhances resistance to general, pitting and crevice corrosion. It is an essential component of many nickel-base alloys and in high-temperature alloys provides resistance to oxidation and sulphidation. It also plays an essential role in low-alloy creep-resisting steels by providing matrix strengthening and stable carbide formation.

Manganese (25) acts as a mild deoxidant, combines with sulphur to form MnS inclusions and is a strengthening element in low-alloy steels. It is also an austenite former and in some austenitic stainless steels (nitronics) is used as an economic substitute for nickel.

Iron (26) is the base element in all low-alloy and stainless steels. It is used in nickel alloys as far as is practicable, to reduce costs, but in general terms it does not promote corrosion resistance.

Cobalt (27) has a corrosion resistance similar to that of nickel in most environments, but because of its high relative cost, it is not used as a primary alloying element in materials designed for aqueous corrosion resistance. On the other hand, cobalt imparts unique matrix-strengthening characteristics to both stainless and nickel-base alloys designed for high-temperature service.

Nickel (28) is the base element in nickel-base alloys and has useful corrosion resistance in its own right in certain environments. However, nickel can accommodate into solid solution larger quantities of critical elements such as chromium, molybdenum, tungsten, etc. than can iron. As a result, nickel-base alloys can offer corrosion resistance in more aggressive environments. This ability to accommodate a wide range of alloying elements is exploited in the development of complex superalloys for very high-temperature service. Nickel is used to stabilise the austenite phase in a wide range of stainless steels and for this reason, the distinction between highly alloyed stainless steels and lower alloyed nickel-base alloys is somewhat blurred. Higher levels of nickel also promote resistance to stress corrosion cracking. Nickel also increases fracture toughness when added to carbon–manganese up to a maximum useful level of about 9%.

Copper (29) can form a complete alloying continuum with nickel, covering all compositions from 100% nickel to 100% copper. In practice, the cupronickel and Monel type alloys are the most widely used, and particularly exploit, the resistance of copper to seawater corrosion and to bio fouling. In stainless steels, copper improves corrosion resistance to reducing acids and can also provide additional strengthening through precipitation hardening.

Niobium (41) combines with carbon to stabilise stainless steels and reduce susceptibility to intergranular corrosion. It also improves resistance to pitting and crevice corrosion in nickel-base alloys and increases strength. In low-alloy steels it acts as a carbide former and improves the creep performance of advanced creep-resisting steels.

Molybdenum (42), like chromium, is an essential alloying component of low-alloy creep-resisting steels and provides both matrix strengthening and stable carbides. In stainless steels it greatly enhances pitting and crevice corrosion resistance, but there are limits as to how much can be accommodated in the iron-base matrix. However, amounts up to almost 30% can be incorporated into nickel-base alloys to give exceptional corrosion resistance in a wide range of aqueous environments.

Tungsten (74) is used in low-alloy steels as both a matrix strengthener and a strong and stable carbide former to give improved creep performance. It is exploited in a few stainless steels, usually in combination with molybdenum, to improve pitting and crevice corrosion resistance. It is also used in both corrosion-resistant and high-temperature nickel-base alloys and in some high-temperature austenitic stainless steels.

Rare earth metals (REM) (57, 58, etc.) are more correctly described as the lanthanides. The most important of these are lanthanum and cerium and it is the latter that is used in some high temperature stainless and nickel-base alloys. REMs help to stabilise and prevent growth and spalling of the oxide film at high temperatures. They are also used in many carbon–manganese and low-alloy steels for inclusion shape control during steel making.

There are three other elements, namely oxygen, sulphur and phosphorus that, while not usually encountered as deliberate alloying elements, can have a significant effect on the performance of a steel or alloy.

Oxygen (8) is always present during steel making and is soluble in molten steel and alloys. Deoxidation is carried using various deoxidants such as Mn, Si, Al and Ti to eliminate any possible porosity and minimise the size and number of non-metallic oxide inclusions remaining in the solid material. High volumes of inclusions can have a significant detrimental influence on mechanical properties and even corrosion resistance.

Sulphur (16) is present in most steels and alloys as a residual from raw material ores and slags. In most high-performance alloys it is desirable to maintain the sulphur as low as possible. High levels can have an adverse effect on weldability and on properties, particularly pitting corrosion resistance. Fortunately, modern steel-making methods combined with desulphurising and inclusion shape control additions, mean that in most corrosion and heat-resistant steels and alloys it is relatively easy to achieve sulphur levels of 0.01%, or even lower.

An exception to the low sulphur rule is those steels and alloys where sulphur and/or selenium are added at levels of about 0.3% to improve machinability (Group E).

Phosphorus (15) is present in most steels and alloys as a residual from raw materials and slag systems. It is a relatively easy element to remove from low-alloy steels during the oxygen steel-making process but in steels and alloys containing significant amounts of chromium, there is the risk that the chromium will be oxidised in preference to the phosphorus. For this reason, phosphorus levels in most stainless steels tend to be between 0.01 and 0.02%. Very low levels are desirable for resistance to temper embrittlement in some low-alloy steels and in these cases levels are usually maintained below 0.01% by careful selection of raw materials and recycled scrap.

Controlled levels of phosphorus are sometime added to carbon steels to improve machinability and corrosion resistance.

Appendix 6: Types of corrosion

Many of the alloys described in this book were designed to be resistant to aqueous corrosion or to operate in high-temperature gaseous environments. Both situations can result in a variety of corrosion mechanisms and the more common ones are outlined below.

Aqueous or wet corrosion

General corrosion – This is uniform attack and is a common form of corrosion. It is characterised by a chemical or electrochemical reaction that takes place uniformly over the whole of the exposed surface. After a period of time, which may be minutes, hours or years, the metal thins to the point where failure occurs.

Pitting corrosion – Pitting is a form of localised corrosion resulting in the formation holes or pits in the metal surface. Once initiated, they can grow rapidly and lead to perforation and failure in a short period of time.

Crevice corrosion – Crevice attack usually takes place at the tight gap between two surfaces (e.g. between a gasket and a joint face). It is sometimes considered to be a particularly severe form of pitting attack and the micro-environment within the crevice can lead to rapid propagation.

Corrosion fatigue – Corrosion fatigue takes place due to the combined effect of fatigue loading on a component in a corrosive environment. Visible evidence of corrosion is not usually present but failure takes place under stresses that normally would not be expected to result in failure.

Stress corrosion cracking (SCC) – This is a form of cracking caused by the simultaneous presence of tensile stresses and a specific corrosive medium. The stresses may result from service loads or residual stresses. There is little evidence of general corrosion and a characteristic is the presence of fine cracks, which can propagate through the material to cause failure. Chloride SCC of austenitic stainless steels is an example.

Intergranular corrosion – This is the selective attack of an alloy at the grain boundaries by a corrosive medium. In some cases this may arise because of elemental segregation or the formation of undesirable phases at grain boundaries. In unstabilised austenitic stainless steels it can occur because of the formation of chromium carbides and the consequent depletion of chromium.

High-temperature corrosion

Oxidation and scaling – This takes place when the maximum service temperature of an alloy is exceeded in air or an oxygen-rich atmosphere. Over a period of time the oxide layer thickens and often spalls off, until metal thinning and failure take place.

Catastrophic oxidation – This can be a problem for alloys containing molybdenum, such as type 316 stainless steel. Refractory metals such as molybdenum, tungsten, etc. can undergo rapid oxidation in oxygen at temperatures above about 700 °C. The exothermic nature of the reaction means that the oxidation process accelerates and large volumes of scale are produced, which can lead to severe damage and distortion if confined.

Sulphidation – This, like oxidation, involves the interaction between a metal and a hot atmosphere, in this case a sulphur-bearing gas. The kinetics are higher than for oxidation because sulphides do not tend to form stable high-melting point films. For this reason the films break down and failure occurs rapidly.

Hot corrosion – This is a phenomenon where two or more media are present and they combine synergistically to produce degradation at a rate much faster than any of the individual factors. Normal oxidation can be greatly accelerated in the presence of sulphides and/or chlorides because the normally stable oxide film is continuously being damaged by lower melting point films, allowing reactions to proceed rapidly.

Carburisation – Carbonaceous atmospheres do not result in scale formation but carbon diffusion takes place into the base alloy. After a period of time, large amounts of chromium carbide will form, resulting in reduced ductility and creep performance. In addition, the local differences in thermal expansion and volume changes between carburised and non-carburised materials can result in cracking and premature failure.

Metal dusting – Atmospheres rich in carbon monoxide compared with carbon dioxide can induce rapid localised damage known as ‘metal dusting’. Whole grains of metal are dislodged and the surface becomes powdery. Damage occurs at temperatures between 500 and 800 °C and it is very much a surface effect, without any oxides present in the reducing conditions. Alloys such as 800 and 300 series stainless steels can be affected.

Halogen attack – The general mechanism is similar to that of oxidation or sulphidation. However, scales do not form because the products tend to be volatile and vaporise. Halogen species are highly mobile in metals at high temperatures and therefore attack can be rapid and lead to early failure.

Bibliography and sources of further information

There are many excellent reference books that the reader can consult for further information and specific data. Some of the more useful ones are:

- *Metallic Materials Specification Handbook*, by Robert B. Ross, published by Chapman and Hall. This book was first published in 1968 but is regularly updated. It covers the full range of alloys and metallic materials.
- *Woldman's Engineering Alloys*, edited by John P. Frick, published by ASM International. This book was first published in 1936 and is regularly updated. It covers the complete range of engineering alloys.
- *Stahlschüssel*, by C.W. Wegst, published by Verlag Stahlschüssel Wegst GmbH. This book is revised and reprinted every three years. It is a German reference book, but much of the text is included in English and French. It covers all grades of steel with the emphasis on European standards.
- *Steel Specifications*, published by the UK Steel Association. This was first published in 1959 and is regularly updated. It is a compilation of steel specifications (and some nickel alloys) and includes British, European and American standards.

ASM International, Ohio USA, publish a number of speciality handbooks edited by J. R. Davis. The ones most relevant to this book are:

- *Alloy Digest Sourcebook – Stainless Steels*, first published in 2000. A major reference book, which includes comprehensive data sheets for more than 250 grades of stainless steel. It covers all the major groups, including many proprietary alloys.
- *ASM Speciality Handbook – Stainless Steels*, first published 1994. A reference book giving detailed information on production, metallurgy, corrosion behaviour, fabrication, microstructure and properties of stainless steels.
- *ASM Speciality Handbook – Nickel, Cobalt and their Alloys*, first published 2000. A reference book on nickel and nickel alloys covering all the main types. (It also includes cobalt and cobalt alloys.)

The Nickel Development Institute (NiDI) is an international non-profit organisation with an interest in nickel stainless steels and nickel alloys. It produces a wide range of technical reports, which are available from The European Technical Information Centre, The Holloway, Alvechurch, Birmingham, B48 7QB, UK.

Metrode Products Ltd and their range of alloyed welding consumables provided much of the inspiration for this book. They have a technical handbook which describes welding consumables and background for virtually all of the alloys in the book. Detailed information is available at www.metrode.com.

In recent years, the Internet has become a serious source of technical information. Virtually all the major producers of steels, stainless steels and nickel alloys have comprehensive websites. Many of these include data sheets for individual grades of steel, which can be downloaded. Most include comprehensive information on mechanical properties, corrosion behaviour and other aspects of performance and fabrication.

A list of the more important producers, particularly those based in Europe and the USA, is given:

- AK Steel – see Armco
- Allegheny Ludlum (USA) – producers of speciality stainless steels. AL prefixes most designations. AL6XN® and AL 29-4® are registered trade names.
  www.alleghenyludlum.com
- Arcelor – see Industeel
- Armco Steel Corp. (USA) is now named as AK Steel. Armco developed Nitronic® high-manganese stainless steels, and 17/4® precipitation hardening steels; both these designations are registered trade names.
  www.aksteel.com
- AvestaPolarit (Europe) – a major European stainless steel producer, formed from the merger of Avesta Sheffield and Outokumpu.
  www.avestapolarit.com
- Carpenter Technology Corp. (USA) – producers of speciality stainless steels and nickel alloys. Registered trade names include Pyromet®, Custom® and 20Cb-3®.
  www.cartech.com
- Corus Steel – formed following the privatisation of British Steel. The engineering steels division supplies the more highly alloyed steels. Registered trade names include Esshete® and Silver Fox®.
- Creusot – see Industeel
  www.corusengineeringsteels.com
- Doncasters – see Paralloy
- Duraloy Technologies Inc. (USA) – producers of speciality stainless steels, particularly cast heat-resisting grades. Registered trade names include Duraloy®, Supertherm®, 22H® and Super22H®.
  www.duraloy.com
- Haynes International (USA) – formerly Cabot Alloys and producers of nickel and cobalt base alloys. Registered trade names include Haynes® and Hastelloy®.
  www.haynesintl.com
- Inco – see Special Metals
- Industeel (Europe) – now part of the Arcelor Steel Group and including Creusot Loire Steel once known as Creusot Loire Industries (CLI). They are producers of a wide range of stainless steels. Trade names include Sirius® and Uranus® and many stainless grades are prefixed with UR.
  www.cli-fafer.com
- Langley Alloys (UK) – manufacturers of stainless steels and cupronickels and now part of the Meighs Group. Trade names include Ferralium® and Marinel®.
  www.meighs.com

- Manoir Industries (Worldwide) – Originally a French company, they are producers of speciality stainless steels particularly cast high-temperature grades. Most grades are prefixed by the name Manaurite®.
  www.manoir-industries.com
- Meighs – see Langley
- Paralloy, now Doncasters Paralloy (UK) – producers of stainless steels, particularly cast high-temperature grades. Most grades are prefixed by the name Paralloy®.
  www.doncasters.com
- Rolled Alloys (USA) – Producers of heat- and corrosion-resistant alloys, usually supplied in the wrought rather than cast form. Most grades are prefixed by the trade name RA®.
  www.rolledalloys.com
- Sandvik (Worldwide) – Originally a Swedish company which produces a wide range of stainless steels. Some grades are prefixed by the trade name Sanicro® and others by SAF®.
  www.steel.sandvik.com
- Schmidt and Clemens (Worldwide) – Originally a German company, which specialises in cast high-temperature stainless steels.
  www.schmidt-clemens.de
- Special Metals (Worldwide) – Originally the International Nickel Company (INCO). Producers of high alloy stainless steels and particularly nickel alloys. Trade names and grade prefixes include Inconel®, Incoloy®, Monel® and Nimonic®.
  www.specialmetals.com
- Sumitomo Steel Corp. (Worldwide) – Originally a very large Japanese steel company. The metals division is active in the supply of stainless pipes and tubes, particularly for the oil and gas industries.
  www.sumitomometals.com.jp
- VDM (Europe) – Originally a German company and now part of the Thyssen-Krupp Group, they are producers of high-alloy stainless steels and nickel alloys. Trade names include Nicrofer®, Cronifer®, Cunifer®, Nimofer® and Nicorros®.
  www.kruppvdm.com
- Weir Materials (UK) – Producers of stainless steels including superduplex grades. Zeron® is a registered trade name and prefix.
  www.weirmaterials.com

Index of generic numbers

(omitting prefix letters)