ISSF
INTERNATIONAL STAINLESS STEEL FORUM

Martensitic Stainless Steels





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1 Introduction

TIM COLLINS
Secretary-General

Following the success of the publication by the ISSF and ICDA of The Ferritic Solution" in 2007, which was intended to promote the development of applications for the growing range of technically and commercially competitive ferritic stainless steels, attention has been channeled towards another understated, but similarly useful, range of stainless steel grades, known as martensitic stainless steels.

With an excellent strength to weight ratio, strong resistance to corrosion, but, particularly, a good hardness, it has been used in a wide range of applications, of which, perhaps, the best known has been knife steels, which are capable of holding a sharp edge.

To provide the right environment for further growth of this range of materials it was necessary to research existing and potential applications, to provide a technical introduction to the material and to provide testimonials from existing producers who have used the material and can talk with authority about its value.

Thanks are due to Thiery Crémailh, Chairman of the ISSF Long Products Committee and his members, for the idea and the contributions which they provided to make this publication so successful, to our wider membership for their support and contributions, and, particularly, to Bernard Héritier, who planned, wrote and marshalled the resources necessary for the essential examples and pictures used in this project. Special thanks are also due to the internationally renowned and respected technical specialist, Dr. Jacques Charles, for kindly agreeing to review the draft and to provide his comments and guidance. Last, but not least, grateful thanks to Jo Claes for her design skills and for preparing the book for the printers.

We commend this book to producers, stockists and end-users, with the hope that they will find it a helpful tool for their own market development activities.

Tim Collins
Secretary-General
International Stainless Steel Forum
Brussels

2 What they say about martensitics

Sara Nubicella
Group Purchase Category Manager
DAB Pumps S.p.A., Italy

DAB pumps produce large vertical pumps. Their shaft must withstand a large torsion force when the pump is switched on, which led to the choice of AISI 420B grade for its high mechanical properties.
We also manufacture hot water circulation pumps. The shafts require a very good wear resistance. Grade AISI 420C offers the optimum performance.

Roberto Arcos Pérez
Technical Manager (CTO)
ARCOS HNOS, S.A., Albacete, Spain

ARCOS knives are produced in Spain with high quality martensitic stainless steel. We used it in many different thickness and formats (sheets or coils), as well as different variations in chemical composition. Thanks to heat treatments, such us hardening and tempering, we are able to obtain an excellent cutting power and durability of our knives edge. Martensitic stainless steel provides high corrosion resistance and makes easier the compliance with the international cutlery standard ISO 8442-1.

Pascale Sol-Bruchon
General Manager
Rousselon Dumas-Sabatier, Thiers, France

We produce top quality knives for professionals and renowned chefs. We selected grade EN 1.4116 +N, a martensitic stainless steel grade with nitrogen addition that offers an outstanding set of properties of which high hardness, good corrosion resistance. Our knives offer a great performance, of which a long life and an excellent cutting performance even after many re-sharpening operations.

Takayuki Osakabe
General Manager, Design Division, ME Business Unit
YAMAHA MOTOR CO., LTD. Shizuoka, Japan

We, Yamaha Motor, utilize stainless steel for several products. Especially, more than half of the Yamaha outboard motors apply martensitic stainless steel. Since the motors are operated in long period on the water, they are expected high corrosion resistance. In addition, as they are used in severe conditions like fishery and transportation for a long time, high durability is also essential. In order to achieve such a high reliability, we believe martensitic stainless steel is one of the best material for them. We will keep using the stainless steel to meet our strict quality standard and offer absolute reliability to our customers in the future.

Masahito Watanabe
President
YOSHIDA METAL INDUSTRY CO., LTD, Niigata, Japan

We have produced kitchen knives made from martensitic stainless steel for whole blade since 1960. Martensitic stainless steel is indispensable to keep sharpness for a long time. Although it was a disadvantage that martensitic stainless steel was difficult to process because of its hardness, our company repeatedly conducted research and product development, produced all-stainless kitchen knives made by integrating handle and blade in 1983. And these products have been highly regarded by our customers for hygiene because there is no gap between handle and blade. In addition, we also produce all-martensitic stainless steel kitchen knives by forging. Many customers are satisfied with sharpness and design of our kitchen knives, but sometimes we take a complaint about rusting. There are some misunderstandings that there are problems with usage such as washing by dishwasher and that stainless steel does not rust. I am considering improving our products using martensitic stainless steel with higher corrosion resistance.

3 “Rediscover the Martensitics”

This family of steels deserves a fresh assessment, as their mix of properties is often underestimated:

High performance engineering steels

The high mechanical properties of the martensitic stainless meet those of engineering steels, and add a most welcome moderate to good corrosion-resistance.
Users of engineering steels may want to consider them rather than having to resort to surface treatments, which are expensive, cause recycling problems and are inefficient once the coating has been damaged or worn out. In addition, some of the martensitic stainless steels are much easier to weld and to heat treat than their low alloyed counterparts.

Excellent tool steels

Wear resistance cannot be associated with hardness only. In many cases, such as abrasion by particle laden fluids, wear results from a mix of erosion and of corrosion processes. High carbon martensitic stainless steels combine high hardness and corrosion resistance, providing an optimal solution for many applications.

Sustainable stainless steels

Martensitic stainless steels typically contain 12 to 17% chromium and nickel in a range from 0 to 5%. The lower nickel content (compared to austenitic stainless steels) offers the secondary advantage of a lower material cost.
Martensitic Stainless Steels, like the other Stainless Steel families, provide a long, low maintenance product life, and it benefits from an excellent recycling rate.

Stainless steels with more stable prices

The major constituents of stainless steels – besides iron – are chromium and nickel. The price of chromium is historically relatively stable, allowing the martensitic – and ferritic – stainless steels to behave likewise.
Martensitic stainless steels thus provide a good price stability, an essential

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requirement of many users.

Martensitics Groups (03-1, 03-2)

Martensitic stainless steels contain more than 10.5% Chromium and their mechanical properties can be adjusted by heat treatment, just like engineering steels.
They fall into 4 subgroups (with some overlap)

1. **Fe-Cr-C steels**: They were the first grades put into use and still widely used in engineering and in wear-resistant applications.
2. **Ni-bearing grades**: in which Ni replaces some of the C. Compared to the previous group, they offer a higher toughness particularly at low temperatures. Their higher Cr content leads to a higher corrosion resistance. Mo additions in groups 1 and 2 improve further the corrosion resistance.
3. **Precipitation hardening stainless steels**: offer the best combination of strength and toughness.
4. **Creep-resisting grades**: with about 11%Cr, differ from subgroup 1 by additions of Co, Nb, V and B which increase of high temperature strength and creep resistance (up to 650°C).

Many standards cover martensitic stainless steels along with the other families (austenitics, ferritics and duplex).
They are usually associated with product forms.
A list of the main EN and ASTM standards is given in Appendix 1 and 2. More standards exist for specific industries and/or applications.

Group 1	Group 2	Group 3	Group 4
<u>1a engineering</u> Cr: 10.5-13% C: 0.1-0.4% Typical grades ASTM: 410, 420 EN: 4006, 4021, 4034 <u>1b wear resistant</u> Cr: 13-17% C: 0.4-1.0% Typical grades: ASTM: 440A/B/C EN: 4125	Cr: 13-17% Ni: 2-5% C: <0.2% Typical grades ASTM: 431 EN: 4057, 4313, 4418	Cr: 15-17% Ni: 3-5% Cu: 3-5% Nb C: <0.1% Typical grade: ASTM: 631 (17-4PH, 15-5PH) EN 1.4542, 1.4545, 1.4534, 1.4594, 1.4596	Cr: 10.5-12% C: <0.1-0.25% Mo: 0.8-1.5% With Co, Nb, V, B additions Typical grades 4913, 4923

Impressive references

Among the success stories of martensitic stainless steels, three typical and extremely demanding applications stand out.

- Aerospace applications, in which high strength, stiffness, reliability and corrosion resistance are demanded. The Electro Slag Remelting (ESR) process allows the use of the grades at their top performance levels.
- Power generation, in which creep resisting grades allow a continuous operation of steam generators and steam turbines up to about 650°C. This is especially important as most of the world's electricity today is produced by steam turbines, in which the energy is provided by fossil fuels, biomass and nuclear fission.

- Oil and gas recovery. 13Cr grades are widely used today for moderate temperatures, CO_2 and H_2S pressure. New grades (most of them proprietary) more resistant to Stress Corrosion Cracking (SCC) and Sulfide Stress Cracking (SSC) are now under development and are expected to bridge the gap between the martensitics and the expensive high corrosion resistant duplex grades in the future.

High quality martensitics

Much intensive research and development has gone into improving the quality and properties of martensitic stainless steels. This can perhaps be best seen in impact properties. Process improvements allow the use of some these grades down to -60°C, making martensitics suitable for building and construction in very cold climates. Producers have now greatly increased and diversified the range of grades/properties to meet the users' needs, often in partnership with customers.

Good machinability lowers the costs

Free machining grades (EN1.4005 and 1.4029) have been around for a long time but suffer from a reduced corrosion resistance. Today, Ca-treated martensitic stainless steels are widely available. They lead to large machinability increases using carbide tools without any significant decrease of corrosion resistance. They are therefore very attractive when machining contributes significantly to the cost of the finished part. The automotive industry, among others, has recognized this potential and is using these grades in a variety of applications.
While most of the martensitic families are soft in the annealed condition and thus easily machined, the precipitation hardening family is hard in the annealed condition. They are still machinable, but for intricate machining, they can be heat treated to a lower hardness.

Magnetic and corrosion resistant

A widely held misconception is that magnetic stainless steels are not "real" stainless steels and will rust like carbon steel. This is nonsense. Purely for reasons of atomic structure, some stainless steels are magnetic and some are not. Corrosion resistance is not a matter of atomic structure but one of chemical composition – in particular chromium content. Magnetism has nothing to do with it.

Perfection is matching the spec

The martensitic family is often selected where high hardness or high strength is required. It is important to match the corrosion resistance of the use to the corrosion resistance of the alloy. It should be noted that the corrosion resistance of the standard martensitic alloys are highest in the hardened condition - generally they should not be used in the annealed (soft) condition. There are some martensitic stainless steels which have roughly the equivalent corrosion resistance of AISI 304. Sometimes a lower corrosion resistance can be tolerated by a reasonable in-service compromise, e.g. advising end-users to clean their product's surface regularly. This is normal practice in the food process industry on knives where the high hardness is required.
In any economic analysis for a martensitic stainless steel, the cost of heat treating the material must be taken into account.

Martensitic special cards

1. **High mechanical properties** at room temperature, higher than those of austenitics, ferritics and duplex, similar to those of engineering steels.
2. **High hardness and wear resistance** of the high Carbon grades
3. **Good creep resistance** of the Co/V/Nb/W/B grades
4. **Higher Stiffness** than Titanium and Aluminium alloys, similar to that of other steels
5. **Moderate to good corrosion resistance** (austenitics being good to excellent)
6. **Magnetic** (including soft magnetic grades)
7. **Thermal conductivity** up to twice that of austenitic stainless steels
8. **Thermal expansion coefficient** about 2/3 of that of austenitic stainless steels
9. **Improved machinability grades** are available, besides free machining grades

4 Corrosion Resistance

Stainless steels are "stainless" because of their chromium content

All steels are prone to corrosion, to varying degrees. However, stainless steels are much more corrosion resistant than carbon steels, thanks to their chromium content. Chromium is the key ingredient in the corrosion resistance of stainless steels.
The corrosion resistance of stainless steels is determined more by chemical composition than by their microstructure. Ni-containing martensitic grades exhibit a better corrosion resistance, because it allows a higher Cr and/or Mo content. This family of grades can be divides into 4 sub-groups:

Group 1 Martensitics are best suited to non-severe conditions, such as inside the home (where the material is either not exposed to water contact or gets regularly wiped dry) or outdoors in contexts where some superficial corrosion is acceptable. In such contexts, this group of Martensitics has a longer life than carbon steel.
Groups 2 and 3 grades show a better corrosion resistance than group 1. They are effective in contexts involving contact with water, in non-severe conditions.
Group 4 Martensitics have a corrosion resistance similar to that of group 1, but are usually used in high temperature steam and to a lesser extent to high temperature automotive applications.

Pitting Corrosion Resistance

A comparison of the corrosion–resistance properties of the martensitic "groups" with those of austenitic type 304 clearly highlights the key role of Chromium and Molybdenum and shows that the corrosion resistance of 304 nickel-containing austenitic grades can be matched by some martensitic grades, as can be seen in Figure 1.

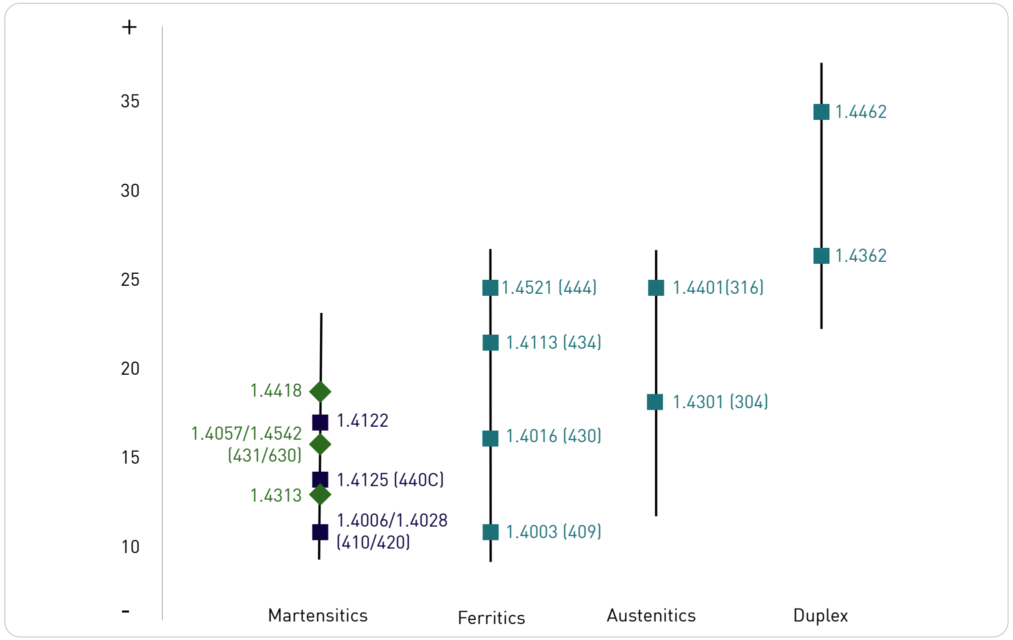

Figure 1 *Pitting corrosion resistance of some grades according the PREN Aperam*

Modified PREN

- The Pitting Resistance Equivalent Number (PREN) is a measure of the relative pitting corrosion resistance of a stainless steel grade in a chloride-containing environment. The higher the PREN value, the more corrosion resistant the grade will be against localized corrosion. It is defined for austenitic grades by PREN = %Cr+3.3%Mo+16%N.
- In martensitic stainless steels, however, some of the Cr may be tied up in Carbides, reducing thereby the amount of available Cr for the passive film.
- Aperam suggested the following formula, which will be used throughout this document:

PREN = %Cr+3.3%Mo+16%N-5%C

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Stress corrosion Cracking (SCC) (04-1 to 04-3)

SCC may take place when the combined action of environmental conditions (such chlorides, H2S, Hydrogen pick-up) and stress (either applied, residual or both) develop the following sequence of events:

i) Pitting occurs

ii) Cracks start from a pit initiation site

iii) Cracks then propagate through the metal in a transgranular or intergranular mode

iv) Failure occurs

Guidance on the use of martensitic stainless steels in H2S service can be found in NACE MR0175/ISO 15156 (see also Appendix 8). A well-known application in which SCC must be taken into account is oil recovery (more details later).
In other applications, SCC is unlikely below Yield Strength levels of 600MPa. SCC may occur above 1000 Mpa if some precautions have not been taken to avoid hydrogen charging in all the processing operations. The aerospace industry has built specifications that guarantee no risk of SCC.

Oxidation Resistance

Unlike the two above types of corrosion, high-temperature "oxidation" occurs at elevated temperatures. When stainless steels are heated their chromium content forms a protective chromium oxide surface "scale" that delays further oxidation. The scale and the metal substrate will have different thermal expansion behaviour, which can affect the scale's stability, especially in service conditions of frequent thermal cycling. The expansion coefficient of the scale is very low and if that of the metal is too high, excessive scale will be generated which will spall or crack when the metal cools and contracts. Thanks to their lower thermal expansion coefficient, martensitic grades are much less prone than austenitic alloys to elevated temperature spalling. Where there is no spalling or cracking, there is no new oxidation.
Creep-resisting martensitic stainless steels are designed for service in high temperature applications up to 650°: steam generators, turbine blades, automotive intake valves and other components.

Improved martensitic grades

New grades have been on the market in the past few years, most of them proprietary. They are therefore not included in the current standards.

- Martensitics with Nitrogen additions are now gaining acceptance. (04-4 to 04-6) As can be seen in the PREN formula, Nitrogen strongly improves the pitting resistance. It also improves the mechanical properties and is an austenite stabilizer just like Nickel. Adding Nitrogen and reducing Carbon and Nickel results in better performance and less expensive grades. The problem, however, lies in the low solubility of Nitrogen in liquid steel and in the δ ferrite phase during solidification. The PESR process (electro-slag remelting under high nitrogen pressure) is the current process that allows nitrogen contents up to 0.4%. Lower nitrogen grades are produced by the conventional AOD process. Figure 2 (from Ugitech) shows the improved pitting potential resulting from a 0.1% Nitrogen addition in martensitic grade EN 1.4116 in the Q&T condition. Aperam reports an even better pitting potential value (470mV) in grade EN 1.4060, a 0,35%C 16%Cr 0,15%N martensitic stainless steel. Typical applications today are found in cutlery, ball bearings, ...

- Super 13Cr and 17Cr proprietary grades have been developed to increase the SCC (Stress Corrosion Cracking) and SSC (Sulphide Stress Cracking) resistance for oil production (04-7 and 04-8). Typical analyses are 13%Cr 5%Ni 2%Mo (by Vallourec) and 17%Cr 5%Ni 2.5%Mo 2.5%Cu (by NSSMC). Their high corrosion resistance (PREN =20), their high mechanical properties (Yield Stress 760MPa min and UTS 860MPa min) and their good weldability will extend the usefulness of martensitics to new applications in the coming years.

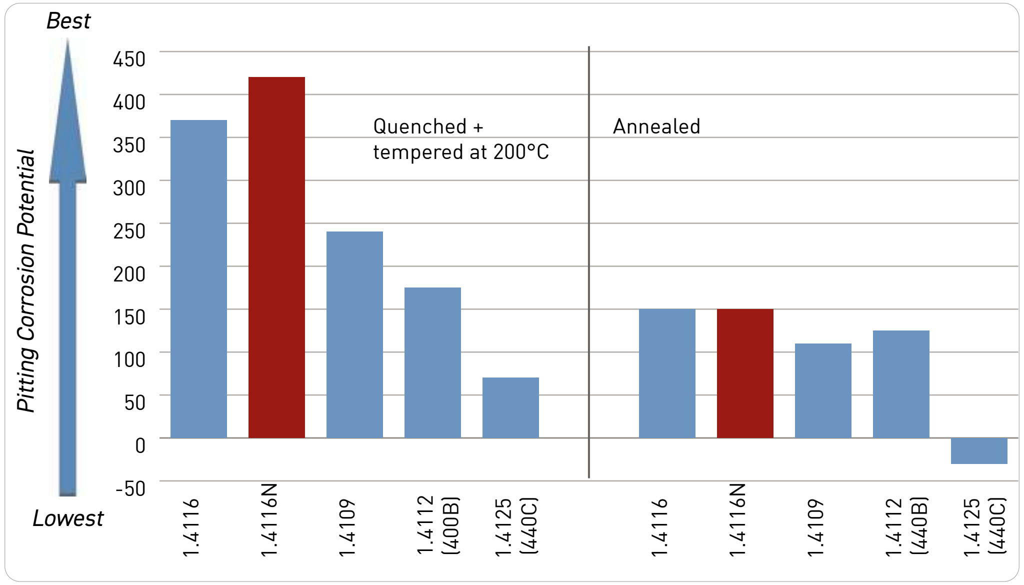

Figure 2 *The Pitting Corrosion Resistance in NaCl 0.02M + pH6.6-23°C*

Avoiding corrosion

Stainless steel's "passive" layer needs oxygen to remain intact. An accumulation of deposits can deprive the steel of oxygen at critical points, which could lead to crevice corrosion. Proper design can greatly reduce its occurrence.
Corrosion sets in when the pH reaches a critically low value (low pH = high acidity).
Pitting corrosion is another -and frequent- form of corrosion characterized by localized damage of the passive layer. It is usually caused by chlorides and/or sulphur compounds (present in industrial, coastal and marine environments). Prevention requires the selection of a stainless steel with adequate corrosion resistance (see Figure 1). Stress corrosion cracking may occur when high stress levels are coupled with aggressive environments. Getting expert advice is recommended. Some localized (pitting) corrosion may be acceptable in certain applications.

Corrosion risk factors

- Embedded particles
- Superficial deposits
- Surface defects
- Structural discontinuities
- Salinity (salty areas, seawater, etc.)
- Increase of temperature
- Highly acidic conditions (strong acids)

Corrosion-preventing factors

- A clean surface
- A smooth surface
- A pre-passivated surface
- Ageing of the surface
- The washing effect (e.g. rain)
- Higher chromium content
- Oxidizing conditions (O_2 - not too strong)

Choice of grade

Martensitic grades can be used in atmospheric environments of moderate corrosive severity. All parameters concerning in-service conditions should be closely considered in selecting the appropriate grade. If slight localised surface rust (pitting corrosion), for example, is of no importance in a certain application environment, a lower-cost grade might well be the correct material choice.

Rules of thumb

In the case of an aggressive environment, select a grade with a higher chromium and/or molybdenum content. Avoid rough surface finishes – favour a fine-polished surface with a low Ra roughness value. Avoid "crevice-like" geometries.

Life Cycle Costing: An Invaluable Guide

The value of carrying out a Life Cycle Costing study on any potential application cannot be stressed too highly. Such a study will often reveal that stainless steel – generally seen as a costly solution – is actually the lower-cost option, viewed in the long-term. Stainless steel's corrosion resistance means longer life, less maintenance, higher resale value, better appearance, etc. Figure 3 shows an example from the oil industry (04-9).
Already widely used in some industries, martensitic grades are nonetheless still being "discovered". The numerous well proven existing applications, however, lead the way for many exciting new possibilities for these fine steels.

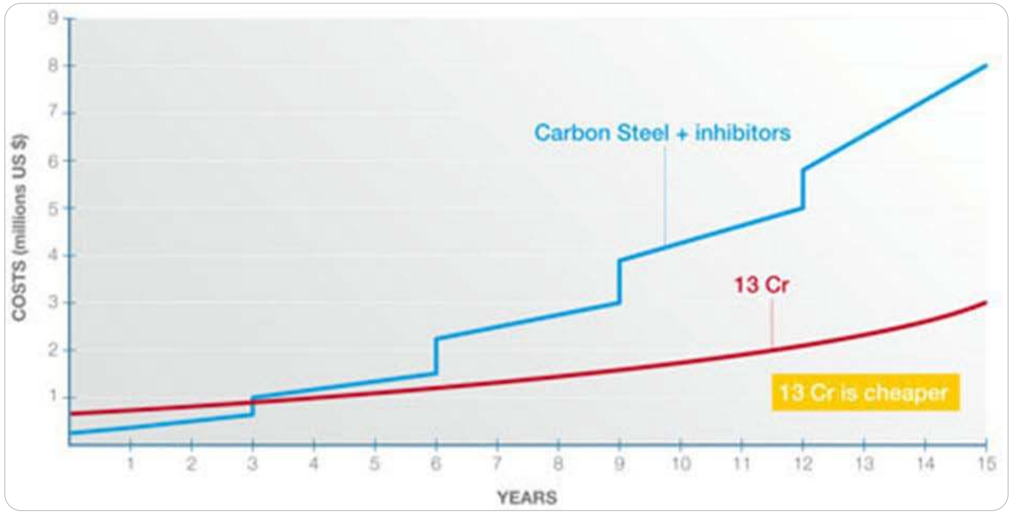

Figure 3 *Comparison of Cost vs time for Carbon steel + inhibitors (+ workovers) and for 13%Cr steel in wet CO2 well*
Source: Vallourec

5 Physical properties

The physical properties of a metallic alloy concern the material's ability to conduct heat, conduct electricity, expand or shrink, etc.
The values for some common martensitic stainless grades are listed in Table 1. A more complete set is available in Appendix 7.
Martensitics are ferro-magnetic.
They also have some other useful advantages over austenitic grades.
Their thermal conductivity, for instance, is notably high. This means that they spread heat comparatively efficiently – which makes them highly suitable for applications such as heat exchangers (tubes or plates) used for instance in steam generators.
The thermal expansion coefficient of martensitic stainless steels is similar to that of carbon steel and much lower than that of austenitic stainless steel. As a result, martensitics distort less when heated.
Last, Young's modulus, which is used to compute the deflection of an elastically loaded member, is higher for steels (including martensitics) than for Al or Ti alloys. When maximum deflection is critical ("stiffness-critical design") besides strength and corrosion resistance, martensitic stainless steels are likely to be selected, for instance in aerospace applications.

EN Designation	EN	AISI	Young's Modulus at 20°C, Gpa	Mean coefficient of thermal expansion between 20 and 100°C $10^{-6}K^{-1}$	Thermal Conductivity at 20°C $W.m^{-1}K^{-1}$	Specific Thermal capacity at 20°C $J.Kg^{-1}.K^{-1}$	Electrical resitivity $10^{-6}\Omega.m$
X12Cr13 X12CrS13 X15Cr13	1.4006 1.4005 1.4024	410	215	10.5	30	460	0.60
X30Cr13	1.4028	420	215	10.5	30	460	0.65
X33CrS13	1.4029	420F	215	10.5	30	460	0.55
X46Cr13	1.4034		215	10.5	30	460	0.55
X50CrMoV15	1.4116		215	10.5	30	460	0.65
X39CrMo17-1	1.4122		215	10.4	15	430	0.80
X105CrMo17	1.4125	440C	215	10.4	15	430	0.80
X90CrMoV18	1.4112	440B	215	10.4	15	430	0.80
X17CrNi16-2	1.4057	431	215	10.0	25	460	0.70
X3CrNiMo13-4	1.4313		200	10.5	25	430	0.60
X4CrNiMo16-5-1	1.4418		195	10.3	30	430	0.80
X5CrNiCuNb16-4	1.4542	630	200	10.9	30	500	0.71
X19CrMoNbVN11-1	1.4913		216	10.5	24	460	
X22CrMoV12-1	1.4923		216	10.5	24	460	
Austenitic	**1.4301**	**304**	**200**	**16**	**15**	**500**	**0.72**
Carbon Steel			**215**	**12**	**50**	**460**	**0.22**

Table 1 *Physical properties for some common martensitic grades.*

6 Applications requiring strength and corrosion resistance

Strength

The typical chemical compositions of the most common grades used for strength are listed in Table 2. For a comprehensive list of standards, please see Appendices 1 and 2.

AISI	EN	C	Cr	Ni	Mo	Other
410	1.4006	0.12	12.5			
416	1.4005	0.12	13.00			S= 0.25
420	1.4021	0.2	13.00			
420	1.4028	0.3	13.00			
420F	1.4029	0.28	12.75			
420	1.4031	0.39	13.5			
	1.4034	0.46	13.5			
	1.4035	0.46	13.25			S= 0.25
430F	1.4104	0.14	16.5		0.4	S= 0.25
431	1.4057	0.17	16.00	2.00		
	1.4313		13.00	4.00	0.5	N ⩾0.02
	1.4418		16.00	5.00	1.15	N ⩾0.02
630	1.4542		16.00	4.00		5C⩽Nb⩽0,45 Cu = 4.00

Table 2 *Average chemical composition of some common grades from EN 10088-1 standard. Appendices 3, 4 and 5 provide a full list.*

Unlike other stainless steel families, the strength of martensitic stainless steels can be adjusted by heat treatment (See Chapter 9), much like engineering steels. It is then up to the designer to choose which one fits best the application. Standards provide several levels of mechanical properties for each grade, from the lowest (full annealing) to the highest (Quenched and Tempered). The minimum Yield Strength of some common grades in the heat treated condition (Quenched and Tempered) are listed in Table 3. A full list is provided in Appendix 9.

EN	AISI	Yield Stress, min (Mpa)
1.4006	410	450
1.4021	420	600
1.4028	420	650
1.4031	420	650
1.4034		650
1.4057	431	700
1.4313		800
1.4418		700
1.4542	630	1000

Table 3 *Minimum Yield stress of usual martensitic stainless steels from EN 10088-3 standard.*

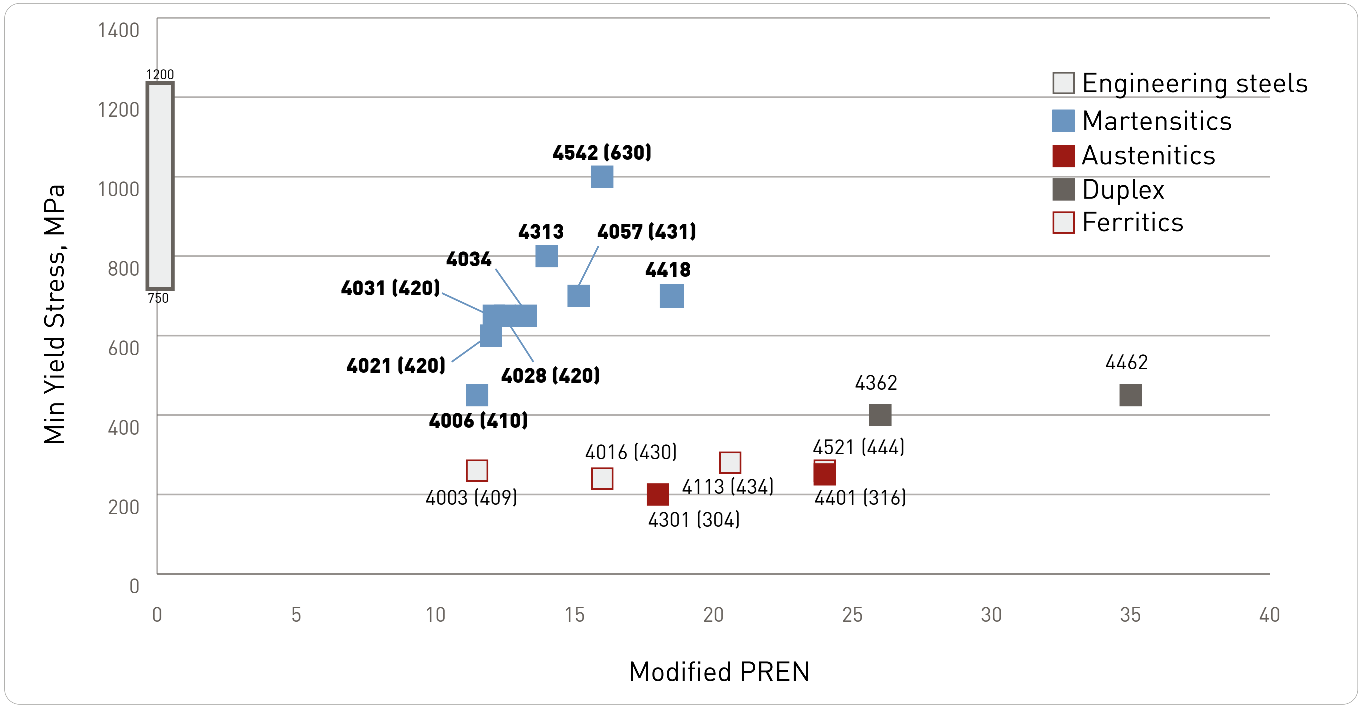

Figure 4 *Minimum Yield Stress vs. Pitting Corrosion Resistance*
Notes: Mechanical properties of stainless steels (martensitics are in the heat treated condition) are those of EN 10088-3: 2014 standard.
Mechanical properties of engineering steels come from EN 10083-3: 2007

In figure 4, the minimum yield stress values of some common martensitic stainless steels are plotted versus the corrosion resistance of the grades, and compared with engineering steels (no corrosion resistance) and ferritic, austenitic and duplex stainless steels.
Martensitic stainless steels achieve a strength level comparable in some cases to engineering steels, with a corrosion resistance that is close to that of the well-known EN 1.4301 (AISI 304) austenitic stainless steel (06-1).
Grades EN 1.4542 (17/4 PH) and EN 1.4418 are particularly attractive in this respect.

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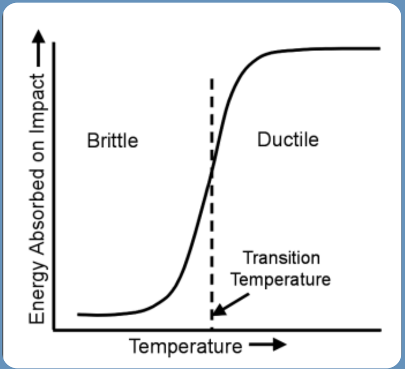
Impact resistance

Present standards specify minimum impact resistance values way below what is guaranteed today by most producers. This is because the impact resistance and the transition temperature between ductile and brittle rupture (DBTT*) is strongly dependent upon processing and know-how. (06-2)
Figure 5 shows the variation of the DBTT with residual Phosphorus and with grain size*. In practice, some martensitics can be used down to −60°C but this must be checked with the materials supplier.

DBTT

All steels, with the exception of the austenitic steels, become brittle at low temperatures. The transition temperature at which this change takes place is called the Ductile to Brittle Transition Temperature (DBTT).



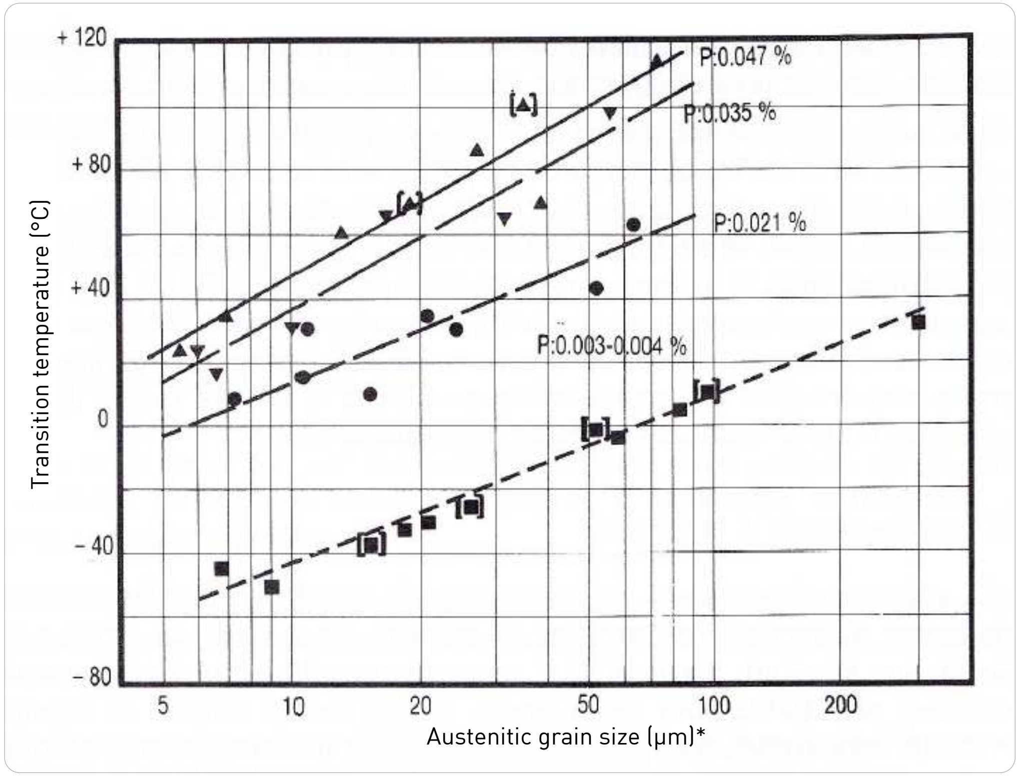


Figure 5 *The variation of the ductile and brittle rupture with residual Phosphorus and with grain size of a 0.2%C 13%Cr martensitic stainless steel.*

** This refers to the microstructure (grain size) of the steel during the "austenitizing" part of the heat treatment (see chapter 9)*

Some applications

Automotive

Martensitic stainless steels are used in a wide variety of applications, which have in common:

- High mechanical properties
- Corrosion resistance to gasoline or to outside environment
- Critical parts

These include

- Shafts of electric motors, (1.4021, 1.4034, 1.4029...)
- Injection pump components
- Common rail parts (1.4057, 1.4418)
- Sensors (1.4542....)
- Intake valves (1.4718)
- High temperature bolts (1.4923)

Suppliers meet the high quality demands of the industry while keeping a competitive cost.

Intake valve. Grade EN 1.4718

Injection pump housing. Grade EN 1.4418.

Pictures courtesy of Deutsche Edelstahlwerke

Shaft of electric motor

Sensor

Oil and gas

Oil drilling: Mud motors

The power section of a mud motor converts the hydraulic power of high pressure drilling fluid into mechanical power for the drill bit. A power section consists of two components: a helical-shaped rotor and a stator. This means the rotational power is provided by a progressing cavity positive displacement mud motor. Increasing the number of stages of a mud motor linearly increases the power output towards the so-called high-performance power sections segment.
The rotors are manufactured from EN 1.4542 (AISI 630 17-4PH) corrosion-resistant stainless steel. The stator is a section of cold drawn, heat-treated steel pipe with a moulded elastomer compound bonded inside.
Mud motors allow directional drilling, all the way from vertical to horizontal and thus improve oil recovery.

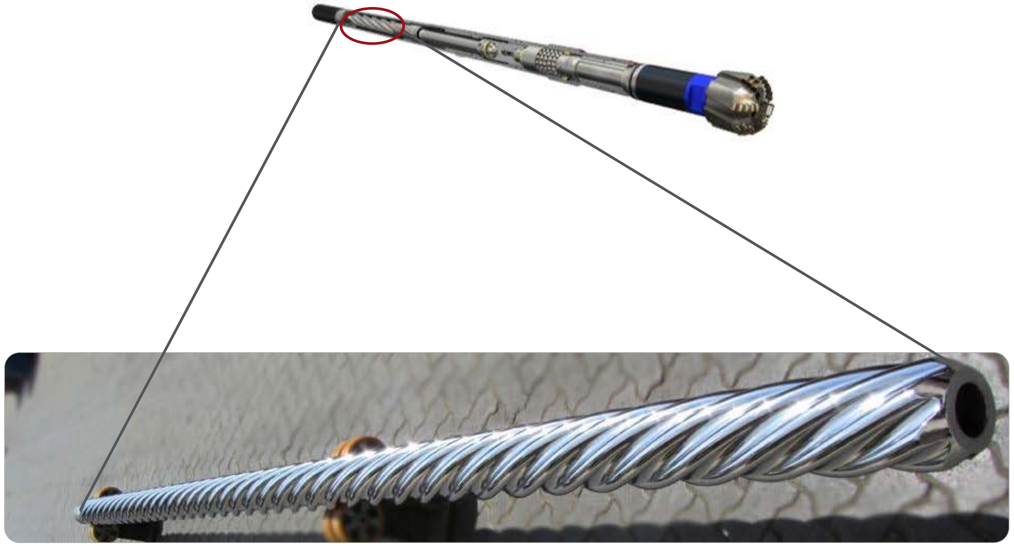
Oil production

Depending upon the degree of corrosion resistance required, materials used for tubing (i.e. the pipes that carry the oil upwards from the well) range from Carbon Steels to Martensitic Stainless Steels to Duplex grades and even to Nickel-base alloys. The rules for the selection of materials are provided by International

Standards (See Appendix 8).
Martensitic stainless steels are suitable for sweet (CO_2) environments, under which standard Carbon and low alloy steels would suffer localized corrosion also called mesa or ringworm corrosion.
While 13%Cr (Type EN 1.4006 - AISI 410) was almost the only martensitic grade used years ago, now new (proprietary) martensitic grades, usually referred to as super martensitics S13Cr and S17Cr are increasingly used as they bridge the gap of performances between 13CR and Duplex materials by providing a larger application domain with regards to temperature, H2S content and Chloride concentration.

Costs

Martensitic stainless steel tubulars cost only half as much as duplex stainless steel and one-fourth to one-tenth as much as high-nickel Alloys.



Rotor section of a mud motor

Using 13Cr Steel Pipe might also be less expensive and more cost-effective than using carbon/low-alloy steel with inhibitors.

Martensitic stainless steels in oil production

The 13Cr Steel pipes are especially attractive for tubing applications in offshore production operations where working space is limited and workover costs are high.

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Architecture, Building and Construction

Rebar

In the reconstruction of the bridge at the Nedujinja Shrine in Japan, grade 410 stainless steel rebar was chosen for its durability as a reinforcement material in concrete structures.
Grade 410 was selected over an austenitic one because of its low thermal expansion properties and low cost.

Nedujinja Shrine bridge with 410 stainless rebar
Picture Courtesy of JSSA

Self-drilling screws

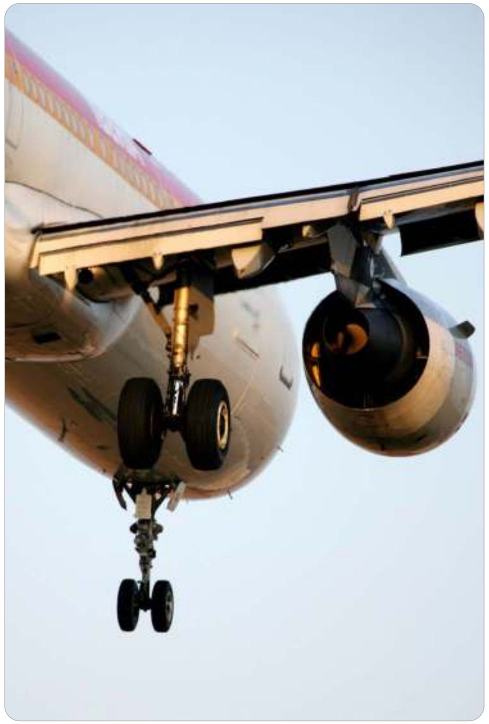
Self Drilling Screws are designed specifically for drilling through thin sheet metal, and are available in a range of head types and drives. A key feature is the self drilling tip which is the part of the screw that drills the hole. The specially shaped flute clears the swarf from the hole for the threaded part of the screw to tap. Grade 410 Stainless Steel is one of the most popular material choices. It offers adequate forming properties and good tip hardness after heat treatment.

Aerospace

High strength martensitic stainless steels and particularly grades EN 1.4542 (AISI 630) are commonly used in aerospace, in a wide variety of applications, of which hydraulic systems, landing gear, shafts, actuators, fasteners, etc...

Reactor ring, calendered and welded then machined to very close tolerances for Airbus A320-330, Boeing 737, 747, 777 and 787
Image courtesy of Centro Inox

Engine of a passenger plane.
Picture courtesy of Centro Inox.



Landing gear components. Grades:
EN: 1.4548 (AISI 630) re-melted and
EN: 1.4545 (AMS 5659, ASTM 564).
Picture courtesy of Iconos.

Mechanical engineering

Boat Shafts (which carry the torque from the engine to the propeller) and rudder shafts are currently in wide use in pleasure boats, workboats, crew boats, fishing trawlers, pilot and patrol boats.

They require a high strength and a corrosion resistance adapted to the environment. Grades EN 1.4542 (AISI 630) and EN 1.4418 are some of the grades frequently used, along with duplex and high nitrogen austenitic grades.

Martensitic stainless steels are used for pump bodies, impellers and shafts, valve bodies, stems etc... pipe fittings, extruders in the food industry, bolts, lithography equipment, conveyor systems, etc...

Centrifugal pump

Submersible water pump. Motor/pump shaft, impeller, sleeves are made of AISI 420 (EN 1.4028) stainless steel.

Valve stem

Centrifugal pump shaft

Valve stem

The high yield stress and Young's modulus combined with corrosion resistance of Grade EN 1.4542 (AISI 630) are ideal for specific applications such as load cells.

Load cell
Courtesy of AS Technologies

Martensitic stainless steel tubes are being promoted for bicycle frames. Their strength/specific weight ratio allows component weight that nearly match Titanium alloy TA6V and Aluminium alloy 7075 – T6.
They are also used high demanding applications such as sailing hardware and mountain equipment in which strength and good corrosion resistance are demanded.

Martensitic Stainless steel tubular frame of bicycles, Grades EN 1.4006 (AISI 410) or 1.4542 (AISI 630) from KVA Stainless. They are also used in sailing equipment for strength and good corrosion resistance

Ship chandler sailing hardware.
HR Forged snap shackle with fixed eye. Grade AISI 630 (EN 1.4542)
Picture courtesy of Wichard SA, France

Ice axe for mountaineering and ice climbing, with a forged stainless steel spike. Spikes are designed to be sharpened like cutting tools. They ensure an excellent grip on rock and an efficient penetration into ice.
Picture courtesy of Petzl SARL.

7 Applications requiring wear resistance and corrosion resistance

Martensitic stainless steels are close to tool steels

High hardness is a requirement for wear resistance but for many applications corrosion resistance is also needed, for instance in cutlery, cutting tools in food processing, injection of abrasive/corrosive polymers, wet abrasion etc...
Martensitic stainless steels after a heat treatment of quenching and stress relieving at temperatures of about 200-300°C (see Chapter 9) can achieve high hardness levels, up to about 60HRc. These values are close to those of tool steels as can be seen in Figure 6. The average analysis of tool steels containing at least 12%Cr in ISO EN 4597 standard is given in Table 4.

Designation	EN	AISI	C	Cr	Mo	V	W
X155CrMoV12-1	1.2379	D2	1.5	12	0.85	0.85	
X210Cr12	1.2080	D3	2.05	12			
X210CrW12	1.2436	D6	2.15	12			0.7
X42Cr3	1.2083	420	0.39	13.5			
X36CrMo17	1.2316	-	0.39	16.5	1.05		

Table 4 *Typical analysis of "stainless" tool steel grades from EN-ISO 4597:2000 standard.*

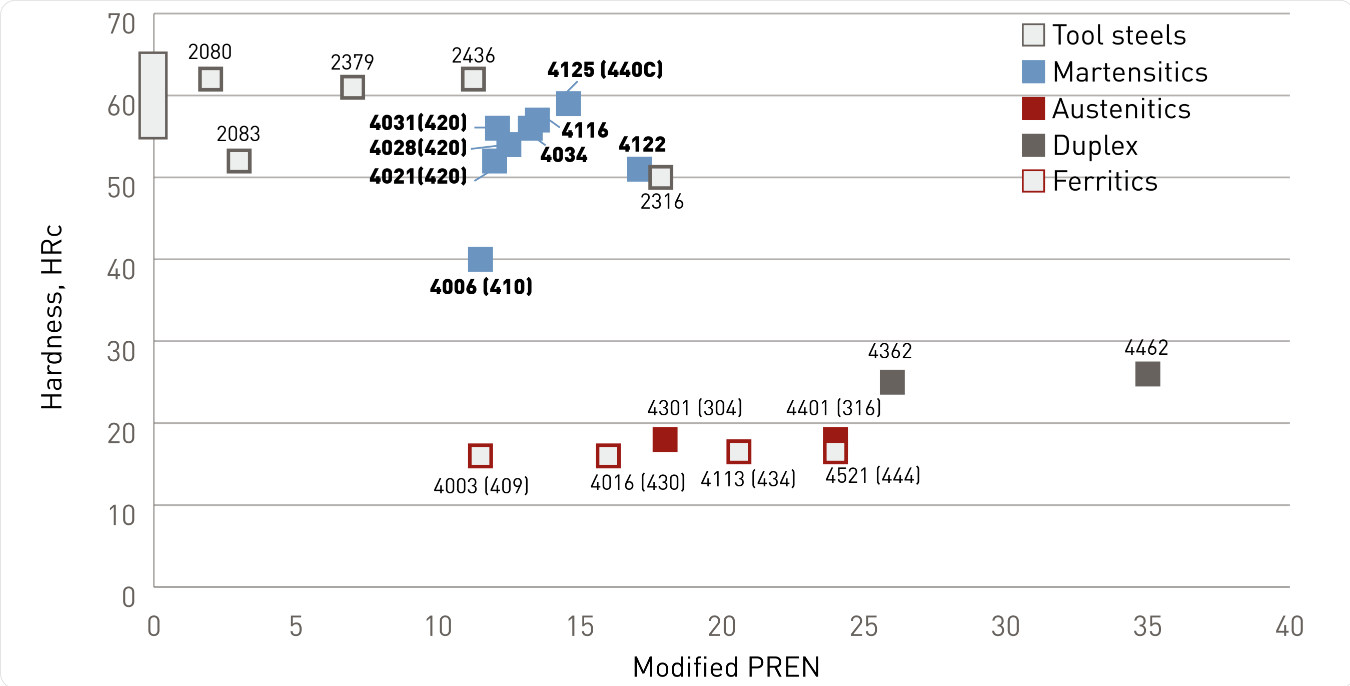


Figure 6 *Hardness vs. Corrosion resistance.*
Note: Although the use of PREN outside its domain of validity is inaccurate, it is fair to say that the value for high C, high Cr tool steels must lie somewhere between stainless and non stainless grades.

Applications

Cutlery and cutting tools

This is one of the well-known uses of martensitic stainless steels.
Different production methods are used to produce table knives. Blades may be cut from a sheet and then sharpened, the handle being usually fixed by rivets. These knives are inexpensive. Higher quality table knives are forged then heat treated and polished, a single piece of steel being used for the blade and for the handle. Grade 1.4028 (AISI 420) is frequently used. Top quality table knives are made of two parts, a forged, heat-treated and polished blade and a handle made of different material such as silver. The martensitic stainless steel grades used for the blade are often EN 1.4122 or 1.4116. They offer a high hardness and a good corrosion resistance.
Very sharp table knives may be dangerous for household applications. Micro serrations of the blade edges offer the best compromise between user safety and good cutting ability.

Professional carving knife, made of martensitic stainless steel grade with 0.5%C and 13%Cr forged and heat treated to a hardness of 55HRc. Courtesy of Sabatier-K.

Obtaining a mirror finish demands a steel free of hard inclusions that cause polishing defects known as "comet tails". Other non-metallic inclusions (such as manganese sulphides) must be reduced as much as possible as they may cause pitting corrosion. Cutlery steels are processed to guarantee a high degree of cleanliness i.e. the absence of non-metallic inclusions.

Damas knife from Masahiro Co Ltd. with special steel core and SUS410 stainless cladding. Picture courtesy of JSSA.

Cutting tools are used in surgery for scalpels, in home appliances such as blenders, in W blades, in food processing applications, for recreational activities, ...

Professional knives

Professional knives demand foremost a good cutting ability for efficiency and to reduce the risk of Repetitive Strain Injuries. This happens when the cutting ability of the knives is low. The force that has to be exerted for a cut is then higher and eventually strains the muscles and the joints of the holder of the carving knife. This is somehow the equivalent of Tennis Elbow well-known to the tennis players.
Cutting tests show that this property is related to

- Hardness (the higher, the better)
- Microstructure (fine grain size and small, well-dispersed carbides)
- Proper sharpening

One of the best grades for this application is EN 1.4116

Foldable pocket knife with a stainless steel damas blade and a cedar wood handle. Picture courtesy of Laguiole

Two-part high quality table knife

Razor blades are made of martensitics

Blender blade

Wear resistant uses

A wide range of uses is related to resistance by erosion/corrosion, i.e. by liquids which may contain solid particles.
Hardness is desirable along with corrosion resistance so that martensitics are one of the best choices.

440C Nozzle for high pressure water cleaner

Cast Pelton wheels and Francis turbines in hydroelectric power plants are often made of martensitic stainless steel EN 1.4313 (ASTM CA6NM). This grade is easy to cast into complex shapes without defects, easy to weld, can be heat treated to a good strength level (see Chapter 9) and exhibits a good resistance to cavitation erosion, which is a special form of corrosion/erosion.

Other turbine components such as spiral case, turbine shaft, guide vanes, stay vanes, etc... are often made of the same grade.

The best known case is that of the Three Gorges Dam in China, the largest hydroelectric power plant of the world to this day. It had installed 32 units of 700MW turbines,which is the largest capacity, largest size of Francis generator set. The Francis turbine runner diameter is 10.05m, height 5.99m, total weight

The Three Gorges Dam in China

445 tonnes. The 15 blades, weighing each 17.6 Tonnes, have been welded to the rings. The stainless steel used is ASTM CA6NM (EN 1.4313).
Pelton runners are also widely used in smaller hydroelectric plants.

Ball, roller or linear bearings

Bearings are usually made of alloy steel 100Cr6. However, for special applications where corrosion resistance is needed, stainless martensitic grades EN1.4125 (AISI 440C, EN 1.4034 (AISI 420C) and EN1.4116 are preferred.
Recently, proprietary high nitrogen grades have been introduced for extremely demanding uses: (07 -1 , 07 – 2)

- X30CrMoN 15-1EN 1.4108 –AMS 5898 for the liquid hydrogen and oxygen fuel pumps of the US Space shuttle
- X40CrMoVN16-2 EN 1.4123 AMS 5925 for liquid hydrogen turbopump bearings of the European space launcher.

A turbine runner of the Three Gorges Power plant

A pelton runner.

Roller bearing

Motorbike and mountain bike brake disk

Stainless steel (Grade 420) does not rust, or at least not to any great extent, is very robust, is tolerant to almost all brakepads and particularly to sintered brake pads. It is highly resistant to wear, it does not shatter and it resists heat very well. The friction coefficients of stainless steel discs and sintered pads went past cast iron around 20 years ago.

Moulds for plastic injection

Injection molds for polymers must be able to produce thousands or even million of parts. Wear resistance is essential. When the polymers are corrosive or laden with solid particles, corrosion resistance is mandatory and martensitic stainless steels are used. Such as EN 1.4057 (AISI 431) or 1.4122. As the shapes of the molds are complex and require expensive machining, the heat treatment is often carried out in the near-finished shape.

When the surface requirements of the plastic parts to be molded is not too severe, high machinability grades (see Chapter 9) are preferred to decrease further the machining costs.

Moulds for glass bottles

Stainless grade EN1.4057 (AISI 431) is the most frequently used for glass molding, as it offers an excellent resistance to thermal cycling and keeps a very clean surface, essential for high quality glass parts. For glasses with a low melting temperature, grade EN 1.4542 (AISI 630) is often preferred. Conversely, special high melting point glasses may require expensive Ni-base alloys.

Petanque balls

This relaxing sport, practiced mostly outdoors during summer vacations, uses chromium-plated or stainless steel balls.
A martensitic stainless steel type EN 4006 (AISI 410) is preferred for top quality sets, as it provides a longer life and does not require any precaution against corrosion. Hardness levels are adjusted to provide, a “soft touch” or a “medium hard” touch as required.

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8 Corrosion and creep-resisting applications

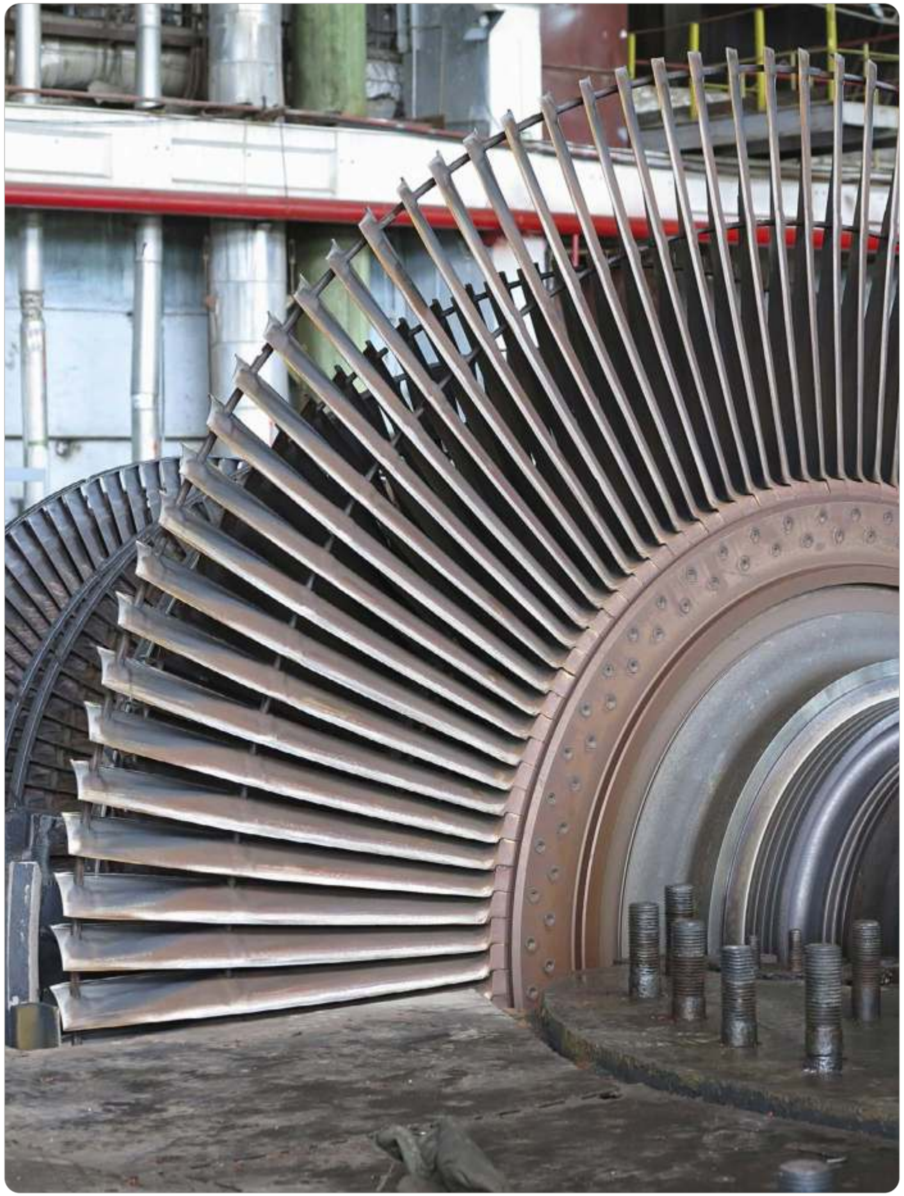
Special martensitic stainless steels are widely used in steam generators and steam turbines for their excellent high temperature properties and creep resistance, up to 650°C. (08-1)
Special austenitic stainless steels and Nickel base alloys are capable of a better performance, but at a much higher cost.
Typical analyses are shown in Table 5. Detailed analyses are given in Appendix 4.

Designation	Number	C	Cr	Mo	Ni	Co	N	Nb	V	W	B
X10CrMoVNb9-1	1.4903	0.10	8.75	0.95			0.03	0.08	0.22		
X11CrMoWVNb9-1-1	1.4905	0.11	9.00	1.00	0.25		0.07	0.08	0.22	1.00	0.0026
X8CrCoNiMo10-6	1.4911	0.08	10.50	0.75	0.70	6.00		0.35	0.25		0.01
X19CrMoNbVN11-1	1.4913	0.20	10.75	0.65	0.40		0.08	0.35	0.20		
X20CrMoV11-1	1.4922	0.20	11.75	1.00	0.55				0.30		
X22CrMoV12-1	1.4923	0.21	11.75	1.00	0.55				0.30		
X20CrMoWV12-1	1.4935	0.20	11.75	1.00	0.55				0.28	0.50	
X12CrNiMoV12-3	1.4938	0.12	11.75	1.75	2.50		0.03		0.33		

Table 5 *Average chemical analyses of creep resisting martensitic stainless steels according to EN 10302 Standard*

As can be seen from this table, special alloying elements have been added to enhance high temperature properties (08-2 to 08-5):

- Molybdenum improves the corrosion resistance, but, as it is a ferrite stabilizer, a small Nickel addition (an austenite stabilizer) offsets it.



- Cobalt and Tungsten act mainly as solid solution strengtheners in the body-centered cubic matrix.
- Niobium (Columbium) and Vanadium are strong carbonitride formers. They form very small precipitates that block the movement of dislocations and of grain boundaries and impart strength and creep resistance.
- Boron in solution (i.e. not as Boron nitrides) reduces the coarsening rate of $M_{23}C_6$ carbides near prior austenite grain boundaries at high temperatures. This in turn slow down the creep* rate and increases the creep life. In order for Boron to be effective, the nitrogen content must be kept low to avoid the formation of boron nitrides, as only the boron in solution is effective.

Stainless steel applications cover turbine blades and other parts, heat exchanger pipes, valve parts, bolts, fittings, various high temperature parts for internal combustion engines.

* At elevated temperatures and constant stress or load, many materials continue to deform at a slow rate. This behaviour is called creep and is very important in engineering as it limits the service life of components.

Tubular heat exchanger

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9 Fabrication

Heat Treatment

For optimum properties, martensitic stainless steels must be heat treated (09-1, 09-2)
Martensitic stainless are available in both the annealed and quenched and tempered condition. In the latter condition they do not require any further heat treatment. This is the simplest way of using them and is perfectly adequate for many applications.
However, processing and particularly machining is much more difficult and costly. It is then advisable to process martensitic stainless steels in the annealed condition and then heat treat the finished or nearly-finished parts
Recommended heat treatment conditions are given in Appendix 10.

Austenitizing

- Has to be carried out at a temperature:
  - High enough to allow sufficient carbide solution in austenite
  - But low enough to avoid grain growth
- A time at temperature of 30 minutes is usually sufficient
- EN 10088-3 provides recommendations for austenitizing temperature range (p.68)
- ASM references are nearly the same

Quenching and martensite formation

- Although austenite transformation into martensite upon cooling does not happen, oil or air cooling are required to prevent undesirable carbide precipitation at austenite grain boundaries during cooling. Such carbide network create Cr-depleted zones at grain boundaries that are weak paths for corrosion. In addition they will decrease the impact properties. Faster cooling rates by water quenching result in an increase of the stresses in the material leading to deformation of the heat treated part and sometimes cracking.
- The temperature Ms at which the martensitic transformation starts upon cooling depends upon the steel composition. The most recent formula is:

  Ms (°C) = 491.2 – 302.6%C – 30.6%Mn - 16.6%Ni – 8.9%Cr + 2.4%Mo – 11.3%Cu + 8.58%Co + 7.4%W – 14,5%Si

  In which the % are expressed in weight % (09-3)

There is no equivalent formula for the temperature Mf at which the martensitic transformation ends. Mf usually lies between 150 and 200°C below Ms.
The major alloying elements of martensitic stainless steels, C, Cr and Ni, depress the Ms temperature. For the most alloyed martensitic grades, Ms can be quite low and as a result the martensite transformation is not complete at room temperature. A further cooling down to about -100°C is necessary. Suppliers offer advice on the optimum heat treatments.

Tempering

- Martensite is hard and brittle, with a high level of internal stresses that can lead to cracking, particularly with High Carbon grades. Post quenching heat treatment is therefore necessary. Hardness decreases with temperature and time as shown in figure 8.
- Stress relieving, at temperatures of about 200-300°C does not decrease significantly the hardness. It is used for cutlery, for cutting tools and sometimes for Moulds
- Tempering is carried out at temperatures above 500°C. (figure 8) It decreases the hardness but restores elongation and toughness

> Stress-relieving and tempering, unlike annealing, do not decrease the corrosion resistance because iron carbides form first and do not reduce the Cr content of the matrix.

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- Annealing treatments are carried out at the highest temperatures compatible with martensite transformation. Their purpose is to obtain the softest material possible, usually for easy machining. For some grades, a double annealing is necessary.

Minimum mechanical properties after heat treatment are given by Standards (ISO, EN, ASTM/AISI).

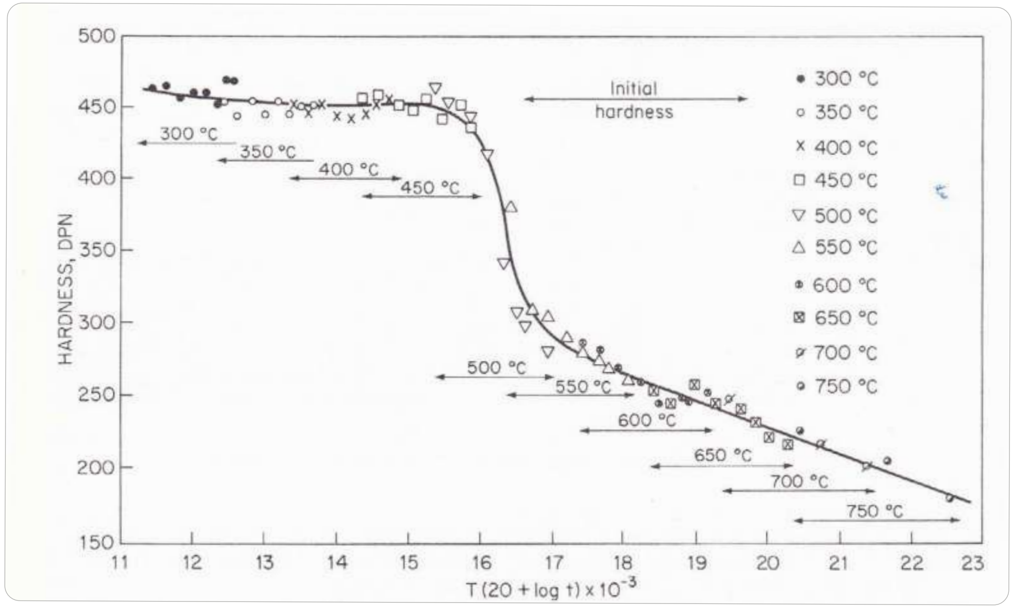


Figure 7 *Influence of tempering on hardness (HV) of a 0;14%C 12%Cr stainless steel. (T: Temperature in °K and t: time in hours) (09 – 2)*

Precipitation hardening

In contrast to martensitic stainless steels which require a tempering heat treatment following quenching from a high temperature, martensitic precipitation-hardening stainless steel such as AISI 630 (17-4PH) only requires a simple low-temperature hardening heat treatment from its solution treated condition. This hardening treatment is sufficiently low in temperature that there is no significant distortion and only superficial discolouration, which can be easily removed by mechanical means, electropolishing or a short pickle. There is a small but known change of dimension during the final heat treatment of these grades.

By varying the hardening treatment between 480 - 620°C for one to four hours, a wide range of properties can be attained, which is shown in Table 6. Note that the name of the treatment, e.g. H900, refers to the holding temperature in oF. It also should be noted that the higher temperature “hardening” heat treatment, e.g. H1150, counterintuitively makes the material less hard than in the solution annealed condition.

The European standards for heat treatment of these grades are shown in Appendix 9 and 10b.

Condition	Hardening		Tensile Stength (MPa)[2]	Yield strength, 0.2% Proof (MPa)[2]	Elongation (% in 50mm)[2]	Hardness		Impact Charpy-V J[2]
	Temp (°C)	Time (h)				Rockwell C[2]	Brinell[2]	
H900	480	1	1310	1170	10	40	388	-
H925	495	4	1170	1070	10	38	375	6.9
H1025	550	4	1070	1000	12	35	331	20
H1075	580	4	1000	860	13	32	311	27
H1100	595	4	965	795	14	31	302	34H1150
H1150	620	4	930	725	16	28	277	41

Values from ASTM A564M; these values apply only to certain size ranges

1 - air cooled
2 - minimum

Table 6 *American standards for heat treatment*

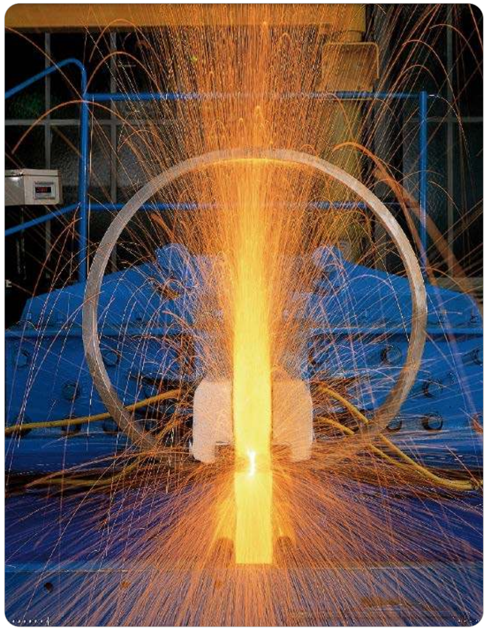
Machining

Machinability is strongly dependent on hardness. The harder the material, the more difficult it is to machine. Very intricate machining, as with injection molds, often leads to the choice of machining in the annealed condition followed by heat treatment. Conversely heat treated bars are preferred for the production of shafts, stems, etc...when little machining is required.
Carbon content increases the hardness. Above a hardness level of about 30HRc, machining is quite difficult. And any significant machining is carried out in the annealed condition.
Non-metallic Inclusion control is the other method for improving machinability.

- Free machining (i.e. with Sulfur additions) grades (Grades EN1.4005 AISI 416, EN 1.4029 AISI 420F) contain MnS inclusions which effectively "lubricate" the interface between the chip and the cutting tool, leading to lower cutting forces and lower tool wear. These grades have been around for a long time but their limitations are well known:
  The MnS inclusions decrease the pitting resistance, which may not be acceptable.
  These inclusions may initiate cracks during and after hot rolling and during heat treatment. This is particularly serious for carbon contents above 0.25%
- Controlled oxides inclusions have gained a wide acceptance now. In the steelmaking process, "Calcium treatment" produces relatively low melting point oxides (such as the "gehlenite" phase in the Al2O3-SiO2-CaO ternary diagram) which act as lubricants (somehow like molten glass) at the chip – tool interface. The temperature required for the lubrication by these oxides is higher than that required for sulphides.

Welding

The most usual processes used are electric arc welding, although all other processes can be used (09-4 and 09-5)
Chromium and carbon content of the filler metal should generally match these elements in the base metal if the mechanical properties of the welds are expected to be close to those of the base metal. When this is not required, types ER 308, ER 309 and ER 310 austenitic filler metals can be used.
Martensitic stainless steels will transform to austenite on heating and are hardened by formation of martensite on cooling. The hardness of the martensite is directly relate to the carbon content. The higher the hardness the higher the tendency toward weld cracking on cooling after welding in the weld deposit or in the heat affected zone (HAZ).
In order to avoid this, preheating and interpass temperature between 200 and 300°C are recommended when the carbon content exceeds 0.1%. A post-weld heat treatment of the welds is recommended in all cases. Welding is not recommended for carbon contents exceeding 0.4%.



Low-Nitrogen shielding gases are also strongly recommended, because nitrogen is a strong austenite stabilizer which will reduce or eliminate all delta ferrite formation during solidification of the fusion zone. A small amount of delta ferrite is beneficial in reducing hot cracking without being too detrimental to the mechanical properties of the welds. In all cases, low Hydrogen filler metals and shielding gases are mandatory to avoid hydrogen-induced delayed cracking

AISI Grade	EN	Coated Electrode	TIG / MIG
410	1.4006	E 410	ER 410, ER 410NiMo
420	1.4028	E 410	E 410, E 420
431	1.4057	E 410	E 410
440 A/B/C	1.4125	Not recommended	Not recommended
630 (17-4PH) and 15-5PH	1.4542	E630 or AMS 5827B	AMS 5826

Table 7 *Recommended filler materials*

Grades EN 1.4313,1.4418 and 1.4542 (AISI 630), all with low Carbon content are popular with fabricators as they are easier to weld than engineering steels and standard stainless martensitic steels.
Providing detailed recommendations that are suitable for every situation is not possible, as those depend upon:

- Part thickness, degree of restraint
- Welds of dissimilar metals
- Properties of the welds required
- Possibility or carrying out pre-post-weld heat treatment of the part and full heat treatments afterwards
- Filler metal options: i) none, ii) homogeneous, iii) austenitic

Advice from an expert, either the steelmaker or the supplier of welding consumables is always available and will help the fabricator to obtain optimum results.

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11 Appendices

Appendix 1: EN standards on martensitic stainless steels

General

- EN 10088-1: 2005: List of Stainless Steels
- ISO 15510:2014: Stainless steels -- Chemical composition
- EN 10302 – 2008: Creep Resisting Steels, Nickel and Cobalt Alloys

Flat products

- EN 10088-2:2014 Stainless steels. Technical delivery conditions for sheet/plate and strip of corrosion resisting steels for general purposes
- EN 10088-4:2009 Stainless steels. Technical delivery conditions for sheet/plate and strip of corrosion resisting steels for construction purposes
- EN 10151:2002 Stainless steel strip for springs. Technical delivery conditions

Long products

- EN 10088-3:2014 Stainless steels. Technical delivery conditions for semi-finished products, bars, rods, wire, sections and bright products of corrosion resisting steels for general purposes
- EN 10088-5:2009 Stainless steels. Technical delivery conditions for bars, rods, wire, sections and bright products of corrosion resisting steels for construction purposes
- EN 10270-3:2011: Steel wire for mechanical springs. Stainless spring steel wire
- EN 10264-4:2002: Steel wire and wire products — Steel wire for ropes — Part 4: Stainless steel wire
- EN 10263-5:2001: Steel rod, bars and wire for cold heading and cold extrusion. Technical delivery conditions for stainless steels
- EN 10090:1998: Valve steels and alloys for internal combustion engines
- ISO 7153-1:1991 Surgical instruments -- Metallic materials -- Part 1: Stainless steel

Tubes & Pipes

- EN 10312: 2005 Welded stainless steel tubes for the conveyance of water and other aqueous liquids - Technical delivery conditions
- EN 10296-2:2005 Welded circular steel tubes for mechanical and general engineering purposes. Technical delivery conditions. Stainless steel
- EN 10297-2:2005 Seamless circular steel tubes for mechanical and general engineering purposes. Technical delivery conditions. Stainless steel
- ISO 9626:1991 Stainless steel needle tubing for the manufacture of medical devices

Forgings

- EN 10250-2:2000 Open steel die forgings for general engineering purposes. Non-alloy quality and special steels

Castings

- EN 10283:2010 Corrosion resistant steel castings
- EN 10293:2005 Steel castings for general engineering uses
- Fasteners:
- EN 10269:2013: Steels and nickel alloys for fasteners with specified elevated and/or low temperature properties

Appendix 2: American standards on martensitic stainless steels

General

- *ASTM A480 / A480M - 16a: Standard Specification for General Requirements for Flat-Rolled Stainless and Heat-Resisting Steel Plate, Sheet, and Strip
- ASTM A484 / A484M – 16: Standard Specification for General Requirements for Stainless Steel Bars, Billets, and Forgings
- ASTM A555 / A555M – 16 : Standard Specification for General Requirements for Stainless Steel Wire and Wire Rods
- ASTM A959 – 11: Standard Guide for Specifying Harmonized Standard Grade Compositions for Wrought Stainless Steels
- ASTM A999 / A999M - 15 : Standard Specification for General Requirements for Alloy and Stainless Steel Pipe
- ASTM A1016 / A1016M – 14: Standard Specification for General Requirements for Ferritic Alloy Steel, Austenitic Alloy Steel, and Stainless Steel Tubes

Flat products

- *ASTM A240 / A240M - 16 : Standard Specification for Chromium and Chromium-Nickel Stainless Steel Plate, Sheet, and Strip for Pressure Vessels and for General Applications
- ASTM A666 - 15: Standard Specification for Annealed or Cold-Worked Austenitic Stainless Steel Sheet, Strip, Plate, and Flat Bar
- ASTM A693 – 13: Standard Specification for Precipitation-Hardening Stainless and Heat-Resisting Steel Plate, Sheet, and Strip

Long Products

- *ASTM A276 / A276M - 16a : Standard Specification for Stainless Steel Bars and Shapes
- ASTM A314 – 15: Standard Specification for Stainless Steel Billets and Bars for Forging
- ASTM A493 – 16: Standard Specification for Stainless Steel Wire and Wire Rods for Cold Heading and Cold Forging
- ASTM A564 / A564M - 13 : Standard Specification for Hot-Rolled and Cold-Finished Age-Hardening Stainless Steel Bars and Shapes
- ASTM A565 / A565M: Standard Specification for Martensitic Stainless Steel Bars for High-Temperature Service
- ASTM A582 / A582M - 12e1: Standard Specification for Free-Machining Stainless Steel Bars

Tubes & Pipes

- ASTM A182 / A182M – 16: Standard Specification for Forged or Rolled Alloy and Stainless Steel Pipe Flanges, Forged Fittings, and Valves and Parts for High-Temperature Service
- ASTM A268 / A268M – 10: Standard Specification for Seamless and Welded Ferritic and Martensitic Stainless Steel Tubing for General Service
- ASTM A511 / A511M - 16 : Standard Specification for Seamless Stainless Steel Mechanical Tubing and Hollow Bar
- ASTM A554 - 16 : Standard Specification for Welded Stainless Steel Mechanical Tubing

Forgings and castings

- ASTM A473 – 16: Standard Specification for Stainless Steel Forgings
- ASTM A743 / A743M - 13ae1 : Standard Specification for Castings, Iron-Chromium, Iron-Chromium-Nickel, Corrosion Resistant, for General Application
- ASTM A487 / A487M – 14 Standard Specification for Steel Castings Suitable for Pressure Service

Fasteners

- ASTM F593 - 13a: Standard Specification for Stainless Steel Bolts, Hex Cap Screws, and Studs
- ASTM F594 - 09(2015) : Standard Specification for Stainless Steel Nuts
- ASTM F836M - 16 : Standard Specification for Style 1 Stainless Steel Metric Nuts (Metric)

Appendix 3: Analyses of the usual EN Standard Grades

Steel designation		% by mass									
Name	Number	C°	Si max.	Mn	P max.	S	Cr	Cu	Mo	Nb	Ni	Others
X12Cr13	1.4406	0.08 to 0.15	1.00	≤1.50	0.040	≤0.015	11.5 to 13.5	-	-	-	≤0.75	-
X12CrS13	1.4005	0.08 to 0.15	1.00	≤1.50	0.040	0.15 to 0.35	12.0 to 14.0	-	≤0.60	-	-	-
X15Cr13	1.4024	0.12 to 0.17	1.00	≤1.00	0.040	≤0.015	12,0 to 14,0	-	-	-	-	-
X20Cr13	1.4021	0.16 to 0.25	1.00	≤1.50	0.040	≤0.015	12.0 to 14.0	-	-	-	-	-
X30Cr13	1.4028	0.26 to 0.35	1.00	≤1.50	0.040	≤0.015	12.0 to 14.0	-	-	-	-	-
X29CrS13	1.4029	0.25 to 0.32	1.00	≤1.50	0.040	0.15 to 0.25	12.0 to 13.5	-	≤0.60	-	-	-
X39Cr13	1.4031	0.36 to 0.42	1.00	≤1.00	0.040	≤0.015	12.5 to 14.5	-	-	-	-	-
X46Cr13	1.4034	0.43 to 0.50	1.00	≤1.00	0.040	≤0.015	12.5 to 14.5	-	-	-	-	-
X46CrS13	1.4035	0.43 to 0.50	1.00	≤2.00	0.040	0.15 to 0.35	12.5 to 14.0	-	-	-	-	-
X38CrMo14	1.4419	0.36 to 0.42	1.00	≤1.00	0.040	≤0.015	13.0 to 14.5	-	0.60 to 1.00	-	-	-
X55CrMo14	1.4110	0.48 to 0.60	1.00	≤1.00	0.040	≤0.015	13.0 to 15.0	-	0.50 to 0.80	-	-	V: ≤0.15
X50CrMoV15	1.4116	0.45 to 0.55	1.00	≤1.00	0.040	≤0.015	14.0 to 15.0	-	0.50 to 0.80	-	-	V: 0.10 to 0.20
X70CrMo15	1.4109	0.60 to 0.75	0.70	≤1.00	0.040	≤0.015	14.0 to 16.0	-	0.40 to 0.80	-	-	-
X40CrMoVN16-2	1.4123	0.35 to 0.50	1.00	≤1.00	0.040	≤0.015	14.0 to 16.0	-	1.00 to 2.50	-	≤0.50	V: ≤1.50 N: 0.10 to 0.30
X14CrMoS17	1.4104	0.10 to 0.17	1.00	≤1.50	0.040	0.15 to 0.35	15.5 to 17.5	-	0.20 to 0.60	-	-	-
X39CrMo17-1	1.4122	0.33 to 0.45	1.00	≤1.50	0.040	≤0.015	15.5 to 17.5	-	0.80 to 1.30	-	≤1.00	-
X105CrMo17	1.4125	0.95 to 1.20	1.00	≤1.00	0.040	≤0.015	16.0 to 18.0	-	0.40 to 0.80	-	-	-
X90CrMoV18	1.4112	0.85 to 0.95	1.00	≤1.00	0.040	≤0.015	17.0 to 19.0	-	0.90 to 1.30	-	-	V: 0.07 to 0.12
X17CrNi16-2	1.4057	0.12 to 0.22	1.00	≤1.50	0.040	≤0.015	15.0 to 17.0	-	-	-	1.50 to 2.50	-
X1CrNiMoCu12-5-2	1.4422	≤0.020	0.50	≤2.00	0.040	≤0.003	11.0 to 13.0	0.20 to 0.80	1.30 to 1.80	-	4.0 to 5.0	N: ≤0.020
X1CrNiMoCu12-7-3	1.4423	≤0.020	0.50	≤2.00	0.040	≤0.003	11.0 to 13.0	0.20 to 0.80	2.30 to 2.80	-	6.0 to 7.0	N: ≤0.020
X2CrNiMoV13-5-2	1.4415	≤0.030	0.50	≤0.50	0.040	≤0.015	11.5 to 13.5	-	1.50 to 2.50	-	4.5 to 6.5	Ti: ≤0.010 V: 0.10 to 0.50
X3CrNiMo13-4	1.4313	≤0.05	0.70	≤1.50	0.040	≤0.015	12.0 to 14.0	-	0.30 to 0.70	-	3.5 to 4.5	N: ≥0.020
X4CrNiMo16-5-1	1.4418	≤0.06	0.70	≤1.50	0.040	≤0.015	15.0 to 17.0	-	0.80 to 1.50	-	4.0 to 6.0	N: ≥0.020
X1CrNiMoAlTi2-9-2	1.4530	≤0.015	0.10	≤0.10	0.010	≤0.005	11.5 to 12.5	-	1.85 to 2.15	-	8.5 to 9.5	Al: 0.60 to 0.80 Ti: 0.28 to 0.37 N: ≤0.010
X1CrNiMoAlTi12-10-2	1.4596	≤0.015	0.10	≤0.10	0.010	≤0.005	11.5 to 12.5	-	1.85 to 2.15	-	9.2 to 10.2	Al: 0.80 to 1.10 Ti: 0.28 to 0.40 N ≤0.020
X5CrNiCuNb16-4	1.4542	≤0.07	0.70	≤1.50	0.040	≤0.015	15.0 to 17.0	3.0 to 5.0	≤0.60	5xC to 0.45	3.0 to 5.0	-

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Appendix 4: Analyses of the creep-resisting EN 10302 Standard grades

Designation		% by mass														
Name	**Number**	**C**	**Si**	**Mn**	**P max**	**S max**	**N**	**Al**	**Cr**	**Mo**	**Nb**	**Ni**	**Ti**	**V**	**W**	**Others**
Martensitic Stainless Steels																
X10CrMoVNb9-1	1.4903	0.06 to 0.12	≤0.50	0.30 to 0.60	0.025	0.015	0.030 to 0.070	≤0.030	8.0 to 9.5	0.85 to 1.05	0.060 to 0.10	≤0.40	-	0.18 to 0.25	-	-
X11CrMoWVNb9-1-1	1.4905	0.09 to 0.13	0.10 to 0.50	0.30 to 0.60	0.020	0.010	0.050 to 0.090	≤0.040	8.5 to 9.5	0.90 to 1.10	0.060 to 0.10	0.10 to 0.40	-	0.18 to 0.25	0.90 to 1.10	B: 0.0005 to 0.0090
X8CrCoNiMo10-6	1.4911	0.05 to 0.12	0.10 to 0.80	0.30 to 1.30	0.025	0.015	≤0.035	-	9.8 to 11.2	0.50 to 1.00	0.20 to 0.50	0.20 to 1.20	-	0.10 to 0.40	≤0.70	B: 0.0005 to 0.015 Co: 5.00 to 7.00
X19CrMoNbVN11-1	1.4913	0.17 to 0.23	≤0.50	0.40 to 0.90	0.025	0.015	0.050 to 0.10	≤0.020	10.0 to 11.5	0.50 to 0.80	0.25 to 0.55	0.20 to 0.60	-	0.10 to 0.30	-	B: ≤0.0015
X20CrMoV11-1	1.4922	0.17 to 0.23	≤0.50	≤1.00	0.025	0.015	-	-	10.0 to 12.5	0.80 to 1.20	-	0.30 to 0.80	-	0.25 to 0.35	-	-
X22CrMoV12-1	1.4923	0.18 to 0.24	≤0.50	0.40 to 0.90	0.025	0.015	-	-	11.0 to 12.5	0.80 to 1.20	-	0.30 to 0.80	-	0.25 to 0.35	-	-
X20CrMoWV12-1	1.4935	0.17 to 0.24	0.10 to 0.50	0.30 to 0.80	0.025	0.015	-	-	11.0 to 12.5	0.80 to 1.20	-	0.30 to 0.80	-	0.20 to 0.35	0.40 to 0.50	-
X12CrNiMoV12-3	1.4938	0.08 to 0.15	≤0.50	0.40 to 0.90	0.025	0.015	0.020 to 0.040	-	11.0 to 12.5	1.50 to 2.00	-	2.00 to 3.00	-	0.25 to 0.40	-	-

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Appendix 5: Analyses of the usual ASTM/AISI Standard grades

UNS Designation	Type	Composition, %									
		Carbon	Manganese	Phosphorus	Sulfur	Silicon	Chromium	Nickel	Molybdenum	Nitrogen	Other elements
S40300	403	0.15	1.00	0.040	0.030	0.50	11.5-13.0	-	-	-	-
S41000	410	0.08-0.15	1.00	0.040	0.030	1.00	11.5-13.5	-	-	-	-
S41040	XM-30	0.18	1.00	0.040	0.030	1.00	11.0-13.0	-	-	-	Cb 0.05-0.30
S41400	414	0.15	1.00	0.040	0.030	1.00	11.5-13.5	1.25-2.50	-	-	-
S41425	-	0.05	0.50-1.00	0.020	0.005	0.50	12.0-15.0	4.0-7.0	1.50-2.00	0.06-0.12	Cu 0.30
S41500	-	0.05	0.50-1.00	0.030	0.030	0.60	11.5-14.0	3.5-5.5	0.50-1.00	-	-
S42000	420	0.15 min	1.00	0.040	0.030	1.00	12.0-14.0	-	-	-	-
S42010	-	0.15-0.30	1.00	0.040	0.030	1.00	13.5-15.0	0.35-0.85	0.40-0.85	-	-
S43100	431	0.20	1.00	0.040	0.030	1.00	15.0-17.0	1.25-2.50	-	-	-
S44002	440A	0.60-0.75	1.00	0.040	0.030	1.00	16.0-18.0	-	0.75	-	-
S44003	440B	0.75-0.95	1.00	0.040	0.030	1.00	16.0-18.0	-	0.75	-	-
S44004	440C	0.95-1.20	1.00	0.040	0.030	1.00	16.0-18.0	-	0.75	-	-

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Appendix 6: Correspondance between grades

Type	ISO-Name	ISO Designation	EN	UNS	AISI	JIS	GB
M	-	X12Cr12		S40300	403	SUS403	S40301
M		X6Cr13	1.4000		410S	SUS410S	S41008
M	4119-410-92-C	X13CrMo13	1.4119()			SUS410J1	
M	4024-410-09-E	X15Cr13	1.4024			SUS410	
M	4006-410-00-I	X12Cr13	1.4006	S41000	410	SUS410	S41010
M	4415-415-92-E	X2CrNiMoV13-5-2	1.4415				
M	4313-415-00-I	X3CrNiMo13-4	1.4313	S41500		SUSF6NM	S41595
M	4642-416-72-J	X13CrPb13	1.4642 ()			SUS410F2	
M	4005-416-00-I	X12CrS13	1.4005	S41600	416	SUS416	
M	4038-420-00-I	X52Cr13	1.4038 ()	S42000			
M	4039-420-09-I	X60Cr13	1.4039()				
M	4419-420-97-E	X38CrMo14	1.4419				
M	4110-420-69-E	X55CrMo14	1.4110				
M	4116-420-77-E	X50CrMoV15	1.4116				S46050
M	4035-420-74-E	X46CrS13	1.4035				
M	4034-420-00-I	X46Cr13	1.4034	S42000			
M	4643-420-72-J	X33CrPb13	1.4643()			SUS420F2	
M	4029-420-20-I	X33CrS13	1.4029	S42020	420F	SUS420F	
M	4031-420-00-I	X39Cr13	1.4031	S42000	420		S42040
M	4028-420-00-I	X30Cr13	1.4028	S42000	420	SUS420J2	S42030
M	4021-420-00-I	X20Cr13	1.4021	S42000	402	SUS420J1	S42020
M	4923-422-77-E	X22CrMoNiV12-1	1.4923				
M	4929-422-00-I	X23CrMoWMnNiV12-1-1	1.4929()	S42200	422	SUH616	
M	4058-429-99-J	X33Cr16	1.4058()			SUS429J1	
M	4019-430-20-I	X14CrS17	1.4019,1.4104	S43020	430F		
M	4418-431-77-E	X4CrNiMo16-5-1	1.4418				
M	4123-431-77-E	X40CrMoVN16-2	1.4123				
M	4057-431-00-X	X17CrNi16-2	1.4057	S43100	431	SUS431	S43120
M	4122-434-09-I	X39CrMo17-1	1.4122				
M	4766-440-77-X	X80CrSiNi20-2	1.4766 ()			SUH4	
M	4025-440-74-J	X110CrS17	1.4025 ()		"440F"	SUS440F	
M	4023-440-04-I	X110Cr17	1.4023 ()	S44004	440C	SUS440C	
M	4041-440-03-X	X85Cr17	1.4041 ()	S44003	440B	SUS440B	
M	4040-440-02-X	X68Cr17	1.1010 ()	S44002	440A	SUS440A	S44070
M	4916-600-77-J	X18CrMnMoNbVN12	1.4916 ()			SUH600	

Appendix 6: Correspondance between grades - continued

Type	ISO-Name	ISO Designation	EN	UNS	AISI	JIS	GB
M-PH	4534-138-00-X	X3CrNiMoAl13-8-3	1.4534	S13800			S51380
M-PH	4594-155-92-E	X5CrNiMoCuNb14-5	1.4594				
M-PH	4532-157-00-I	X8CrNiMoAl15-7-2	1.4532	S15700			
M-PH	4542-174-00-I	X5CrNiCuNb16-4	1.4542	S17400	"630"	SUS630	S51740
M-PH	4568-177-00-I	X7CrNiAl17-7	1.4568	S17700	"631"	SUS631	S51700
M-PH	4457-350-00-X	X9CrNiMoN17-5-3	1.4457 ()	S35000			S51750
M-PH	4530-455-77-E	X1CrNiMoAlTi12-9-2	1.4530				
M-PH	4596-455-77-E	X1CrNiMoAlTi12-10-2	1.4596				
M-PH	4645-469-10-U	X2CrNiMoCu AlTi12-9-4-3	1.4645 ()	S46910			
M-PH	4644-662-20-U	X4NiCrMoTiMnSiB26-14-3-2	1.4644 ()	S66220			

Appendix 7: Physical properties of martensitic stainless steels (EN 10088-1: 2005 standard)

Steel Designation		Density	Modulus of elasticity at					Mean coefficient of thermal expansion between 20° and				Thermal conductivity at 20°C	Specific thermal capacity at 20°C	Electrical resistivity at 20°C	Magnetiz-able
Name	Number	kg/dm³	20°C	100°C	200°C	300°C	400°C	100°C	200°C	300°C	400°C	W / m * K	J / kg * K	Ω * mm² / m	
			GPa					10^{4} x K^{-1}							
X12Cr13	1.4006	7.7	215	212	205	200	190	10.5	11.0	11.5	12.0	30	460	0.60	
X12CrS13	1.4005	7.7	215	212	205	200	190	10.5	11.0	11.5	12.0	30	460	0.60	
X15Cr13	1.4024	7.7	216	213	207	200	192	10.5	11.0	11.5	12.0	30	460	0.60	
X20Cr13	1.4021	7.7	215	212	205	200	190	10.5	11.0	11.5	12.0	30	460	0.60	
X30Cr13	1.4028	7.7	215	212	205	200	190	10.5	11.0	11.5	12.0	30	460	0.65	
X29CrS13	1.4029	7.7	215	212	205	200	190	10.5	-	11.5	-	30	460	0.55	
X39Cr13	1.4031	7.7	215	212	205	200	190	10.5	11.0	11.5	12.0	30	460	0.55	
X46Cr13	1.4034	7.7	215	212	205	200	190	10.5	11.0	11.5	12.0	30	460	0.55	
X46CrS13	1.4035	7.7	215	212	205	200	190	10.5	11.0	11.5	12.0	30	460	0.55	
X38CrMo14	1.4419	7.7	215	212	205	200	190	10.5	11.0	11.5	12.0	30	460	0.62	
X55CrMo14	1.4110	7.7	215	212	205	200	190	10.5	11.0	11.5	12.0	30	460	0.62	
X50CrMoV15	1.4116	7.7	215	212	205	200	190	10.5	11.0	11.0	11.5	30	460	0.65	
X70CrMo15	1.4109	7.7	215	212	205	200	190	10.5	11.0	11.0	11.5	30	460	0.65	
X40CrMoVN16-2	1.4123	7.7	195	199	192	177	-	10.4	10.6	10.8	11.1	24	430	0.90	
X14CrMoS17	1.4104	7.7	215	212	205	200	190	10.0	10.5	10.5	10.5	25	400	0.70	yes
X39CrMo17-1	1.4122	7.7	215	212	205	200	190	10.4	10.8	11.2	11.5	15	430	0.80	
X105CrMo17	1.4125	7.7	215	212	205	200	190	10.4	10.8	11.2	11.5	15	430	0.90	
X90CrMoV18	1.4112	7.7	215	212	205	200	190	10.4	10.8	11.2	11.5	15	430	0.80	
X17CrNi16-2	1.4057	7.7	215	212	205	200	190	10.0	10.5	10.5	10.5	25	460	0.70	
X1CrNiMoCu12-5-2	1.4122	7.7	200	195	165	175	170	10.4	10.8	11.2	11.5	16	450	0.75	
X1CrNiMoCu12-7-3	1.4423	7.7	200	195	185	175	170	10.4	10.8	11.2	11.5	16	450	0.75	
X2CrNiMoV13-5-2	1.4415	7.8	200	195	185	175	170	10.9	-	11.1	-	16	500	0.71	
X3CrNiMo13-4	1.4313	7.7	200	195	185	175	170	10.5	10.9	11.3	11.5	25	430	0.60	
X4CrNiMo16-5-1	1.4418	7.7	200	195	185	175	170	10.3	10.8	11.2	11.5	15	430	0.80	
X1CrNiMoAlTi12-9-2	1.4530	7.7	195	187	178	171	-	10.0	10.3	10.7	11.2	16	500	0.71	
X1CrNiMoAlTi2-10-2	1.4596	7.7	195	187	178	171	-	10.0	10.3	10.7	11.2	16	500	0.71	
X5CrNiCuNb16-4	1.4542	7.8	200	195	185	175	170	10.9	-	11.1	-	16	500	0.71	
X7CrNiAl17-7	1.4506	7.8	200	195	185	175	170	13.0	13.5	14.0	-	16	500	0.80	
X5CrNiMoCuNb145	1.4594	7.8	200	195	185	175	170	10.9	-	11.1	-	16	500	0.71	
X5NiCrTiMoV925-15-2	1.4606	7.9	211	206	200	192	193	16.5	16.9	18.0	17.5	14	460	0.91	no

Appendix 8: Martensitic stainless steels in oil production

Standards (API, NACE, NORSOK ...) define which steels and which Corrosion Resistant Alloys may be used, depending on the oilfield characteristics, i.e. H2S, CO2, Chlorides, pH and Temperature.

Some relevant Standards:

- MR 0175/ISO 15156 « Petroleum and Natural Gas Industries - Materials for use in H2S-Containing Environments in Oil and Gas Production »
- API 5CRA « Specification for Corrosion-resistant Alloy Seamless Tubes for Use as Casing, Tubing, and Coupling Stock Technical delivery conditions«
- ISO 13680-2000 « Petroleum and natural gas industries-Corrosion-resistant alloy seamless tubes for use as casing, tubing and coupling stock-Technical delivery conditions »
- NORSOK Standard M-001

Martensitic stainless steels are used when a moderate corrosion resistance is required, i.e. 10kPa H2S max and pH greater or equal to 3.5 and Temperature max 90°C.

The environment being prone to SSC and SCC, this is one of the few instances in which very low mechanical properties are demanded, i.e. Maximum hardness of 22HRc for all materials.

Appendix 9 Mechanical properties at room temperature of some heat treated martensitic steels from EN 10088-3:2014-12 standard

Name	Number	Condition	Min 0,2% Yield stress, MPa	Ultimate Tensile Strength, MPa	Elongation at rupture, min
		Standard grades			
X12Cr13	1.4006	A	-	≤730	-
		QT650	450	650-850	15
X12CrS13	1.4005	A	-	≤730	-
		QT650	450	650-850	12
X15Cr13	1.4024	A	-	≤730	-
		QT650	450	650-850	15
X20Cr13	1.4021	A	-	≤760	-
		QT700	500	700-850	13
		QT800	600	800-950	12
X30Cr13	1.4028	A	-	≤800	-
		QT850	650	850-1000	10
X39Cr13	1.4031	A	-	≤800	-
		QT800	650	800-1000	10
X46Cr13	1.4034	A	-	≤800	-
		QT800	650	800-1000	10
X17CrNi16-2	1.4057	A	-	≤950	-
		QT800	600	800-950	12
		QT900	700	900-1050	10
X38CrMo14	1.4419	A	-	≤760	-
X55CrMo14	1.4110	A	-	≤950	-
X3CrNiMo13-4	1.4313	A	-	≤1100	-
		QT700	520	700-850	15
		QT780	620	780-980	15
		QT900	800	900-1100	12
X50CrMoV15	1.4116	A	-	≤900	-
X4CrNiMo16-5-1	1.4418	A	-	≤1100	-
		QT760	550	760-960	16
		QT900	700	900-1100	16
X14CrMoS17	1.4104	A	-	≤730	-
		QT650	500	650-850	10
X39CrMo1	1.4122	A	-	≤800	-
		QT750	550	750-950	10

Appendix 9 Mechanical properties at room temperature of some heat treated martensitic steels from EN 10088-3:2014-12 standard - continued

Name	Number	Condition	Min 0,2% Yield stress, MPa	Ultimate Tensite Strength, MPa	Elongation at rupture, min
Special grades					
X29CrS13	1.4029	A	-	≤800	-
		QT850	650	850-1000	9
X46CrS13	1.4035	A	-	≤800	-
X70CrMo15	1.4109	A	-	≤900	-
X2CrNiMoV13-5-2	1.4415	QT750	650	750-900	18
		QT850	750	850-1000	15
Precipitation hardening grade					
X5CrNiCuNb16-4	1.4542	AT	-	≤1200	-
		P800	520	800-950	18
		P930	720	930-1000	16
		P960	790	960-1160	12
		P1070	1000	1070-1270	10

For sections ≤160mm

A: Annealed
QT: Quenched and tempered
AT: Solution Annealed
P: Precipitation hardened

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Appendix 10a: Recommended heat treatments for martensitic stainless steels according t
EN 10088-3 Standard [a]

Steel designation		Hot forming		Heat treatment symbol	Annealing		Quenching		Tempering
Name	Number	Temperature °C	Type of cooling		Temperature[1] °C	Type of cooling	Temperature[2] °C	Type of cooling	Temperature °C
Standard grades									
X12Cr13	1.4006	1100 to 800	air	+A	745 to 825	air	-	-	-
				+QT650	-	-	950 to 1000	oil, air	680 to 780
X12CrS13	1.4005			+A	745 to 825	air	-	-	-
				+QT650	-	-	950 to 1000	oil, air	680 to 780
X15Cr13	1.4024		slow cooling	+A	750 to 800	furnace, air	-	-	-
				+QT650	-	-	950 to 1030	oil, air	700 to 750
X20Cr13	1.4021			+A	745 to 825	air	-	-	-
				+QT700	-	-	950 to 1050	oil, air	650 to 750
				+QT800	-	-	950 to 1050	oil, air	600 to 700
X30Cr13	1.4028			+A	745 to 825	air	-	-	-
				+QT850	-	-	950 to 1050	oil, air	625 to 675
X39Cr13	1.4031			+A	750 to 850	furnace, air	-	-	-
				+QT800	-	-	950 to 1050	oil, air	650 to 700
X46Cr13	1.4034			+A	750 to 850	firnace, air	-	-	-
				+QT850	-	-	950 to 1050	oil, air	650 to 700
X17CrNi16-2	1.4057	1100 to 800	slow cooling	+A[c]	680 to 800	furnace, air	-	-	-
				+QT800[d]	-	-	950 to 1050	oil, air	750 to 800 + 650 to 700[d]
				+QT900	-	-	950 to 1050	oil, air	600 to 650
X38CrMo14	1.4419			+A	750 to 830	furnace, air	-	-	-
X55CrMo14	1.4110			+A	750 to 850	furnace, air	-	-	-
X3CrNiMo13-4	1.4313	1150 to 900	air	+A[e]	600 to 650	furnace, air	-	-	-
				+QT700	-	-	950 to 1050	oil, air	650 to 700 + 600 to 620
				+QT780	-	-	950 to 1050	oil, air	550 to 600
				+QT900	-	-	950 to 1050	oil, air	520 to 580
X50CrMoV15	1.4116	1100 to 800	sl., cool.	+A	750 to 850	furnace, air	-	-	-
X4CrNiMo16-5-1	1.4418	1150 to 900	air	+A[e]	600 to 650	furnace, air	-	-	-
				+QT760	-	-	950 to 1050	oil, air	590 to 620[f]
				+QT900	-	-	950 to 1050	oil, air	550 to 620

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Appendix 10a: Recommended heat treatments for martensitic stainless steels according to EN 10088-3 Standard [a] - continued

Steel designation		Hot forming		Heat treatment symbol	Annealing		Quenching		Tempering
Name	Number	Temperature °C	Type of cooling		Temperature[b] °C	Type of cooling	Temperature[b] °C	Type of cooling	Temperature °C
X14CrMoS17	1.4104	1100 to 800	air	+A	750 to 850		-	-	-
				+QT650	-	-	950 to 1070	oil, air	550 to 650
X39CrMo17-1	1.4122	1100 to 800	slow cooling	+A	750 to 850	furnace, air	-		
				+QT750	-	-	980 to 1050	oil	650 to 750
Special grades									
X29CrS13	1.4029	1100 to 800	slow cooling	+A	740 to 820	air	-	-	-
				+QT850	-	-	950 to 1050	oil, air	625 to 675
X46CrS13	1.4035			+A	750 to 850	-	-	-	-
X70CrMo15	1.4109			+A	750 to 800	furnace, air	-	-	-
X2CrNiMoV13-5-2	1.4415	1150 to 900	air	+QT750	-	-	950 to 1050	oil, air	600 to 650 + 500 to 550
				+QT850	-	-			
X53CrSiMoVN16-2	1.4150	1200 to 1000	slow cooling	+A	800 to 850	furnace, air	-	-	-
				+QT	-		950 to 1050	oil + deep freezing at -80°C	180
X40CrMoVN16-2	1.4123	1200 to 1000	slow cooling	+A	800 to 850	furnace, air	-	-	-
				+QT	-		950 to 1050	oil + deep freezing at -80°C	180
W105CrMo17	1.4125	1100 to 900	slow cooling	+A	780 to 840	furnace, air	-	-	-
X90CrMoV18	1.4112	1100 to 800		+A	780 to 840		-	-	-

a. Temperatures of annealing, quenching and tempering shall be agreed for simulated heat-treated test pieces

b. If heat treatment is carried out in a continuous furnace, the upper part of the range specified is usually preferred, or even exceeded

c. Double annealing might be advisable

d. In the case that the nickel is at the lower side of the chemical composition, a single tempering at 620°C to 720°C may be sufficient

e. Tempering after martensitic transformation

f. Either 2 x 4 h or 1 x 8 h as a minimum time

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Appendix 10b: Recommended heat treatments for martensitic precipitation hardening corrosion resisting steels according to EN 10088-3 Standard [a]

Steel designation		Hot forming		Heat treatment symbol	Solution annealing		Precipitation hardening
Name	Number	Temperature °C	Type of cooling		Temperature[b] °C	Type of cooling	Temperature °C
Standard grades							
X5CrNiCuNb16-4	1.4542	1150 to 900	furnace, air	+AT[c]	1030 to 1050	oil, air	-
				+P800	1030 to 1050		2 h 760 °C/air + 4 h 620 °C/air
				+P930	1030 to 1050		4 h 620 °C/air
				+P960	1030 to 1050		4 h 590 °C/air
				+P1070	1030 to 1050		4 h 550 °C/air

a. Temperatures of solution annealing shall be agreed for simulated heat-treated test pieces

b. If heat treatment is carried out in a continuous furnace, the upper part of the range specified is usually preferred, or even exceeded

c. Not suitable for direct application, prompt precipitation hardening after solution annealing is recommended to avoid cracking.

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