WORKING WITH STAINLESS STEELS - VOL 1 OF 2

Main Category:	Materials Engineering
Sub Category:	-
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MAT-125 EXAM PREVIEW

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Exam Preview:

1. According to the reference material, long products represent about 75% of world stainless steel consumption. They consist typically of bars, wires, standard sections (round, square, rectangular) and special sections (angle irons, U, T and I beams).
    a. True
    b. False
2. Which of the following type of corrosion matches the description: when certain materials are heated between 500 and 800 °C, the grain boundaries can become "sensitized" and undergo preferential attack when subsequently exposed to a corrosive medium?
    a. Pitting corrosion
    b. High temperature corrosion
    c. Intergranular corrosion
    d. Crevice corrosion
3. According to the reference material, uniform corrosion is observed only when the stainless steel is in the active state, i.e. when a passive layer is unstable.
    a. True
    b. False
4. Using Table 1.1.1 - Pitting corrosion resistance of different stainless steels in tap water and sea water, which of the following grades of stainless has the highest resistance index in tap water?
    a. 1.4016
    b. 1.4521
    c. 1.4510
    d. 1.4306

5. According to the reference material, at pressures of the order of ___ bars and temperatures above 600 °C, 12% Cr martensitic grades are usually used.
    a. 150
    b. 200
    c. 250
    d. 300
6. Three-roll forming machines are used to pro-duce components such as cylinders from sheet. Machines designed for mild steels can usually be employed for stainless grades, but their capacity will be reduced by about __%.
    a. 15
    b. 30
    c. 45
    d. 60
7. Slitting is a mechanical cutting technique in which material is removed along a path whose width is determined by that of the tooling.
    a. True
    b. False
8. Using Table 1.2.1 - Major families of stainless steels, which of the following families of stainless steel matches the description: The YS of these grades in typically in the range 215 to 360 N/mm^2 and their UTS from 600 to 800 N/mm^2, with elongations from 40 to 55%?
    a. Ferritic
    b. Martensitic
    c. Austenitic
    d. Duplex austenitic-ferritic
9. According to the reference material, Austenitic stainless steels have high strain hardening rates, and in the cold worked condition their strength tends to induce rapid tool wear.
    a. True
    b. False
10. Hot forming of austenitic-ferritic duplex stainless steels must imperatively be performed above ___ °C. If the temperature is maintained above this value throughout the forming operation and if the subsequent cooling is rapid, further annealing is not necessary.
    a. 800
    b. 850
    c. 900
    d. 950

1 Stainless steels

1.1 Forms of corrosion

The alteration of metals and alloys due to interaction with the surrounding medium is called *corrosion*. The attack begins at the surface of the metal, i.e. at its boundary with the environment, and then propagates inwards by different mechanisms.

Among the metallic materials that withstand corrosion, the stainless steels show excellent resistance in a large number of media, due to a phenomenon known as *passivity*. Stainless steels are protected from their environment by the formation of a very thin *passive film* or *passive layer* at the surface, strongly bonded to the substrate, which prevents further direct contact between the metal and its more or less aggressive surroundings.

In order for the passivity phenomenon to occur in a stable manner, the stainless steel must contain a minimum amount of chromium of the order of 11%. Moreover, with this level of chromium, if the passive film is damaged locally, for example due to a scratch, it has the fundamental property of being able to heal itself in numerous different media. However, if the stainless steel grade has been poorly chosen for the medium concerned, *passivity breakdown* can occur, and the material corrodes.

There are a number of characteristic types of corrosion, and these are outlined below.

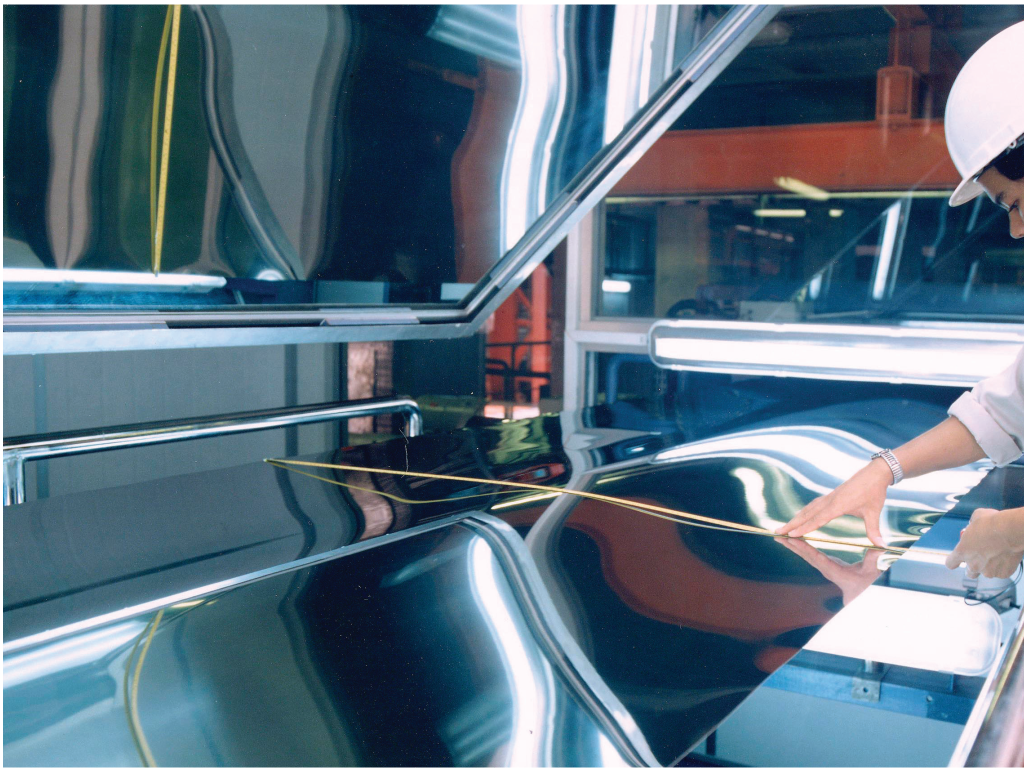


Photo 1: Bright annealing line – inspection stand

Photo 2: Atomium Brussels. The renovated spheres are now clad with sandwich panels made of 1.2 mm outer skin of X2CrNiMo17-12-2/1.4404 stainless steel grade – Brussels (B)

Uniform corrosion

Strictly speaking, uniform corrosion is observed only when the stainless steel is in the active state, i.e. when a passive layer is unstable. In this case, dissolution occurs uniformly over the whole of the surface, leading to a regular decrease in metal thickness and a loss in weight.

Data concerning uniform corrosion are collected in corrosion tables giving the behaviour of stainless steels in different *acid media*, generally free from impurities. Consequently, these data are not valid for all the possible media in which the steels are liable to be employed. They merely serve as guidelines for orienting the initial choice of material, which must be confirmed by consulting a corrosion specialist.

Localized corrosion

Stainless steels can undergo four types of localized corrosion, namely pitting, crevice corrosion, intergranular corrosion and stress corrosion cracking.

Pitting corrosion

This type of attack occurs in a very limited region of the steel surface, the remainder of which is protected by a passive film. Local rupture of the passive film is observed, and if self healing does not occur, a corrosion *pit* develops and can eventually lead to complete perforation of the metal. It is therefore important to avoid the occurrence of this phenomenon by choosing the appropriate grade of stainless steel for the prevailing service conditions (fig. 1.1.1).

The type of medium most liable to promote pitting corrosion is undoubtedly sea water, but so-called “tap” or “fresh” waters can also be aggressive. The parameters that affect the resistance to pitting corrosion are :

- the surface condition of the material (low roughness is beneficial);
- the major alloying elements, namely chromium, molybdenum and nickel;
- the “minor” elements capable of modifying the non-metallic inclusions present in the metal.

From an electrochemical standpoint, it can be shown that a critical *pitting potential* exists on the anodic polarization curve for an alloy, beyond which localized corrosion can be initiated. For a given medium (e.g. tap water, sea-water), the pitting potential can be used to rank different steel grades in terms of their resistance to this type of attack. Thus, in tap water at 25 °C, with a typical NaCl content less than 1.2 g/l (i.e. a molarity* of the order of 0.02 M) and a pH of 6.6, the results shown in Table 1.1.1 are obtained.

In sea water at 70 °C, which is much more corrosive, the NaCl content being of the order of 30 g/l (i.e. 0.5 M), the ranking obtained is given in Table 1.1.1.

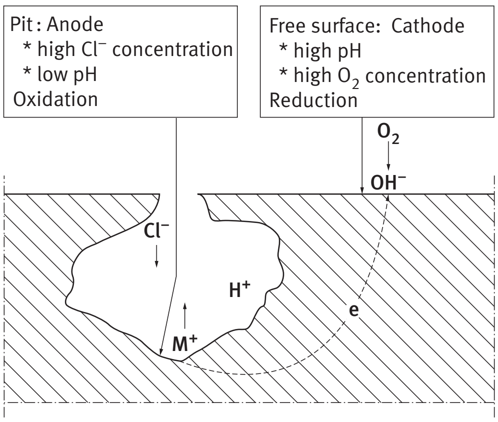


Fig. 1.1.1 - Schematic representation of the growth of a pit in a chloride-containing medium

O_2 : oxygen molecule
OH^- : hydroxyl ion
Cl^- : chloride ion
H^+ : hydrogen ion
M^+ : metal ion
e : electron

Grade: standard designation EN 10088-2	Resistance index (function of the pitting potential)	
	Tap water	Sea water
X6Cr17 / 1.4016	2.5	
X3CrTi17 / 1.4510	4.5	0.5
X2CrMoTi18-2 / 1.4521	7.0	2.0
X2CrNi19-11 / 1.4306	5.0	1.0
X2CrNiMo22-5-3 / 1.4462		4.0
X2CrMoTi29-4 / 1.4592		6.0 (Absence of pitting)

Table 1.1.1 - Pitting corrosion resistance of different stainless steels in tap water and sea water

(*) *The mole (“mol” abbreviation) is the quantity of a substance which contains one gram formula weight of the substance. One mole of any substance contains 6.10^{23} (Avogadro’s number) molecules or atoms. Formerly called one gram molecule. The molarity of a solution is the concentration expressed as the number of moles of the solute in 1 liter of solution.*

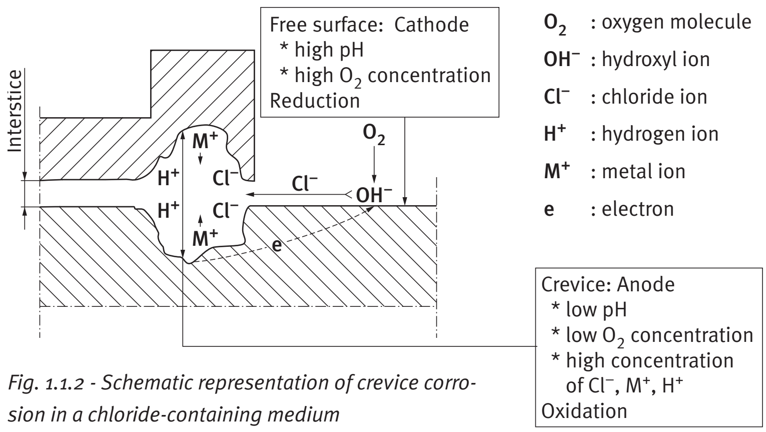


Fig. 1.1.2 - Schematic representation of crevice corrosion in a chloride-containing medium

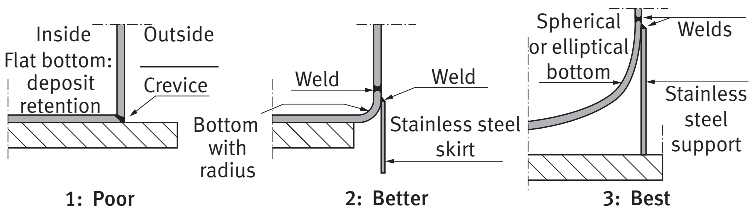


Fig. 1.1.3 - Welded vessel bottom designs

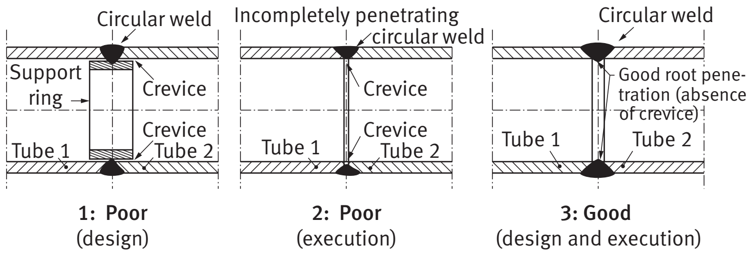


Fig. 1.1.4 - Butt-welded tubes

Depassivation pH	Acidity	Grade: Standard designation EN 10088-2
1	Very high	X2CrNiMo22-5-3 / 1.4462
1.1		X2CrMoTi29-4 / 1.4592
1.2		X1NiCrMoCu25-20-5 / 1.4539
1.8	High	X2CrNiMo17-12-2 / 1.4404
2.1		X5CrNi18-10 / 1.4301
2.5	Moderate	X3CrTi17 / 1.4510
3.0		X6Cr17 / 1.4016

Table 1.1.2 - Values of the depassivation pH for the principal grades of stainless steel in a standard solution

Crevice corrosion

As its name indicates, this type of attack occurs in *crevices* or confined spaces, due either to component or assembly design, or to the presence of deposits formed during service (fig. 1.1.2). The confined or semi-occluded region within a crevice promotes the accumulation of chemical species and the gradual acidification of the medium, facilitating breakdown of the passive film in the locally more aggressive environment. When the pH* in this zone reaches a critical value called the "depassivation pH", corrosion begins. The incubation time before the onset of corrosion depends on the shape (severity) of the crevice. The depassivation pH is used to characterize the ability of an alloy to withstand crevice corrosion. The lower the depassivation pH, the greater the corrosion resistance. Values of the depassivation pH for the principal grades of stainless steel in a standard solution are given in Table 1.1.2.

Crevice corrosion can be prevented by:

a) appropriate design of equipment to avoid crevices (fig. 1.1.3 and 1.1.4);
b) systematically eliminating solid deposits (scale) formed during service;
c) avoiding the use of rubber joints, whose poor adhesion to the metal can create a crevice;

(*) *The* pH *is a measure of the acidity or hydrogen ion content of an aqueous solution. A* pH *of the order of 7 corresponds to a neutral medium, while a much lower value, such as 3, represents an acidic medium, and values greater than 7 indicate alkaline or basic solutions. The definition of the* pH *is such that it varies on a logarithmic scale, i.e. a unit change in* pH *represents a ten-fold difference in concentration.*

d) the suitable choice of material. In particular, austenitic stainless steels (Fe-Cr-Ni alloys) show better resistance than ferritic grades (Fe-Cr alloys). However, the major alloying element used to combat crevice corrosion is molybdenum, to the extent that an Fe - 18% Cr - 2% Mo ferritic stainless steel has better resistance than an Fe - 18% Cr - 8% Ni austenitic alloy.

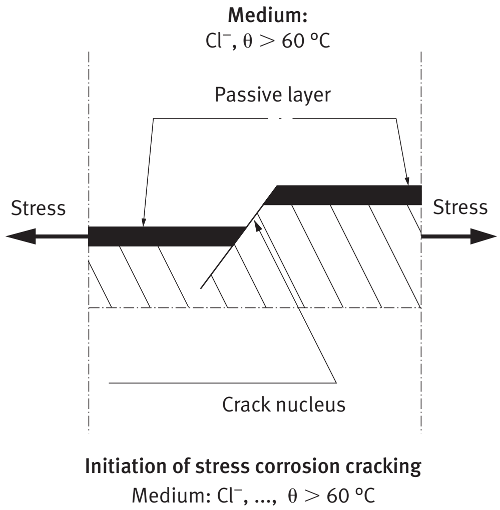
Stress corrosion cracking

Stress corrosion cracking is a process whereby the combination of a mechanical load and a corrosive environment can lead to the initiation of cracks, sometimes after a long incubation period, which can subsequently propagate rapidly and cause failure of the equipment concerned (fig. 1.1.5). The phenomenon is often difficult to detect before cracking has reached a stage where it threatens the life of the installation. The measures to be taken to avoid the occurrence of stress corrosion cracking are:

a) the use, whenever possible, of ferritic grades, which are generally insensitive to this type of corrosion;

b) if the medium is aggressive, the use of either a duplex austenitic-ferritic grade or an austenitic alloy with high nickel and molybdenum contents;

c) attenuation of residual stresses by performing a stress relieving treatment on the equipment before putting it into service, and limitation of operating loads (particularly due to vibrations, thermal expansion, etc.).



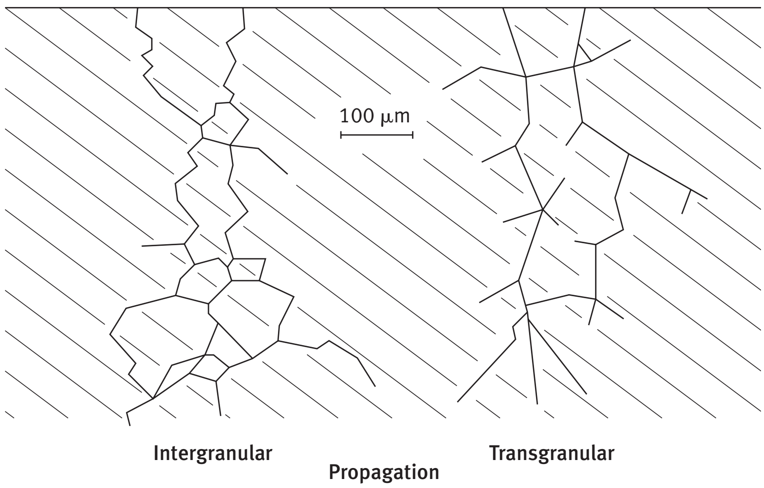


Fig. 1.1.5 - Schematic representation of stress corrosion cracking

Intergranular corrosion

When certain materials are heated between 500 and 800 °C, the grain boundaries can become "sensitized" and undergo preferential attack when subsequently exposed to a corrosive medium. This often occurs during welding operations, in the region of the heat affected zone (HAZ) (fig. 1.1.6) which has been exposed to temperatures in this range. A number of remedies are available for preventing intergranular corrosion:

a) For austenitic alloys (Fe-Cr-Ni or Fe-Cr-Ni-Mo), the choice of a grade with either a low carbon content ($C < 0.03\%$) or the addition of a "stabilizing" element such as titanium.
b) For ferritic alloys (Fe-Cr or Fe-Cr-Mo), it is imperative to choose a grade stabilized with either titanium or niobium.
c) If a stainless steel has become sensitized, its structure can be regenerated by an annealing treatment followed by rapid cooling, the appropriate temperature being 700 to 800 °C for ferritic materials and 1050 °C for austenitic grades.

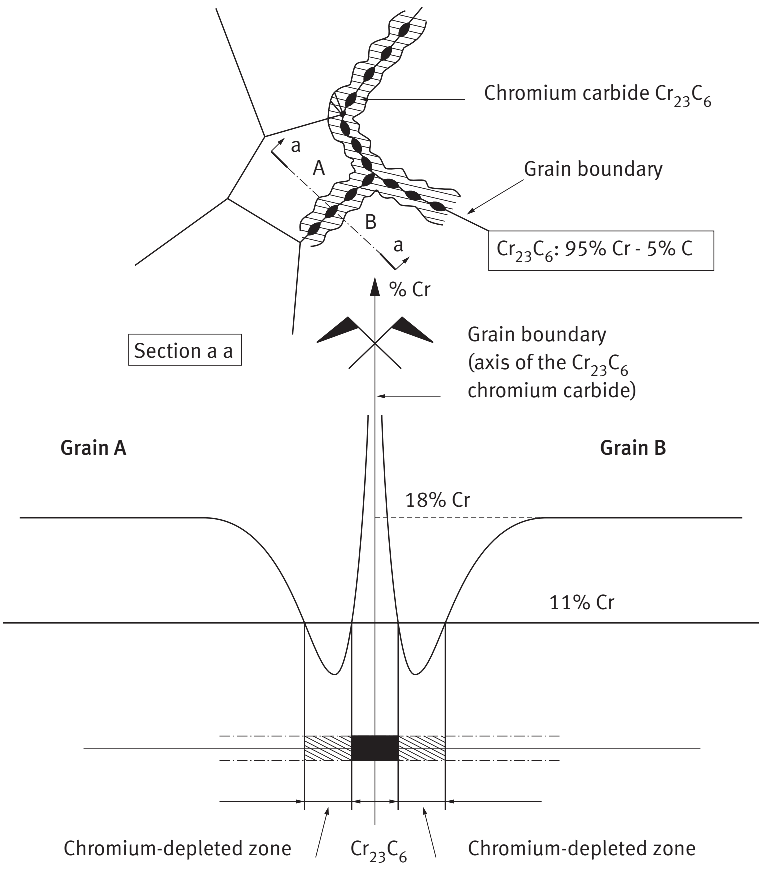


Fig. 1.1.6 - Schematic representation of sensitization to intergranular corrosion due to chromium depletion at grain boundaries in a type X5CrNi18-10 / 1.4301 stainless steel

High temperature corrosion

There is no really strict definition of what constitutes the "high temperature" region, but for the typical applications of stainless steels, the lower threshold is commonly considered to be about 500 °C. In this range, the corrosion mechanisms are different depending on the oxidizing potential of the atmosphere. Highly "oxidizing" gaseous atmospheres include air, oxygen, water vapor, sulfur and its oxides (SO_2 and SO_3), carbon dioxide (CO_2), nitrogen oxides (NO_x) and chlorine. "Reducing" gases are those containing hydrogen, hydrogen sulfide (H_2S), carbon monoxide (CO), hydrocarbons, ammonia, etc. Molten salts can be either oxidizing or reducing towards stainless steels. Finally, certain molten metals can cause corrosion by direct dealloying effects.

"Oxidizing" atmospheres

When stainless steels are heated in an oxidizing atmosphere, the presence of chromium leads to the formation of a protective scale, based on the chromium oxide Cr_2O_3, sometimes overlain by a layer of spinel, such as $FeCr_2O_4$.

The difference in thermal expansion between the oxide and the metal substrate has an important effect on the stability of the scale, particularly when the service conditions involve frequent thermal cycling. It is essentially for this reason that ferritic (Fe-Cr) grades often perform better than austenitic (Fe-Cr-Ni) alloys under severe thermal cycling conditions, since the expansion coefficient of austenite is about 1.6 times that of ferrite, while the value for the scale is very small. Table 1.1.3 gives the recommended maximum service temperatures for applications involving oxidizing atmospheres.

Grade EN 10088-2	Limiting service temperature (°C)	
Standard designation	Continuous	Cyclic
Austenitic grades		
X5CrNi18-10 / 1.4301	930	870
X8CrNi25-21 / 1.4845	1150	1030
Ferritic grades		
X6Cr17 / 1.4016	820	870
X2CrMoTi29-4 / 1.4592	1090	1170

Table 1.1.3 - Recommended maximum service temperatures in oxidizing atmospheres for ferritic and austenitic stainless steels

The addition of at least 2%, and possibly up to 5 or 6% of aluminum, together with small quantities of cerium, lanthanum and/or yttrium, produces a tenaceous and highly protective alumina scale. For example, ferritic alloys containing about 20% Cr together with aluminum and rare earth additions of this sort are used for metal catalyst supports for automobile exhaust gas purification systems. In this application, when the engine is at full speed, the temperature can reach nearly 1000 °C, while the gas contains nitrogen oxides (NO_x), hydrocarbons (HC), volatile organic compounds (VOC) and carbon monoxide (CO), which are converted by catalytic reaction to "non-polluting" species, such as CO_2, H_2O, N_2 and O_2.

"Reducing" atmospheres

Among the commonest types of "reducing" atmosphere are those rich in carbon monoxide or hydrocarbons, which can promote carburizing. In addition to chromium, nickel and silicon are effective alloying elements for improving the resistance to this type of attack, and their combined action has been quantified in terms of an index given by the formula % Ni + 9 x % Si. A common low temperature form of carburizing is the phenomenon known as "metal dusting", in which the metal disintegrates at the surface due to excessive absorption of carbon deposited from the gas.

Nitriding can occur at high temperatures due to reaction with the atomic nitrogen produced by the cracking of ammonia in contact with the metal surface. Since nitrogen has a strong affinity for titanium, aluminum and chromium, it will preferentially form nitrides within the metal. In order to ensure a sufficiently protective oxide scale to limit nitriding, nickel contents greater than 35% are generally necessary. However, a 21% Cr – 11% Ni grade containing cerium has been found to show good resistance in cracked ammonia up to 1100 °C.

In atmospheres containing hydrogen sulfide at temperatures above 800 °C, nickel is detrimental, since it forms a low melting point eutectic Ni/Ni_3S_2, and the best results are obtained with ferritic grades.

Finally, in hydrogen-containing atmospheres, the pressure plays an important role in the risk of hydrogen uptake. At pressures of the order of 300 bars and temperatures above 600 °C, 12% Cr martensitic grades are usually used.

1.2 The stainless steel family

The major families of stainless steels

The table below summarizes the principal families of commercially available stainless steels, i.e. those produced in large quantities and which cover more than 90% by volume of all market requirements. The high productivity manufacturing route typically involves electric arc furnace melting, refining in an argon – oxygen – decarburizing (A.O.D.) converter, hot rolling on a strip or Steckel mill, initial annealing, continuous pickling, cold rolling on a Sendzimir type mill, continuous final annealing, then finishing.

• Martensitic grades	
– carbon ≥ 0.1% – 12 to 18% chromium	Stainless steels capable of undergoing an austenite to martensite transformation on quenching. Depending on the composition and heat treatment, the hardnesses obtained can range from 40 to 60 HRC
• Ferritic grades	
– 0.02 to 0.06% carbon – 0 to 4% molybdenum – 11 to 29% chromium	The Yield Strength (YS) of these grades is typically in the range 250 to 380 N/mm² and their Ultimate Tensile Strength (UTS) from 410 to 700 N/mm², with elongations from 20 to 32%. They cannot generally be hardened by heat treatment.
• Austenitic grades	
– 0.015 to 0.10% carbon – 0 to 4% molybdenum – 7 to 25% nickel – 17 to 20% chromium	The YS of these grades in typically in the range 215 to 360 N/mm² and their UTS from 600 to 800 N/mm², with elongations from 40 to 55%. Their high ductility gives them a remarkable capacity for forming.
• Heat resisting austenitic grades	
– carbon ≤ 0.2% – 11 to 22% nickel – 19 to 26% chromium	The mechanical properties of these alloys are similar to those of the ordinary austenitic grades. However, due to their higher carbon contents, they conserve good strength at high temperature.
• Duplex austenitic-ferritic grades	
– 0.02% carbon – 3% molybdenum – 22% chromium – 5.5% nickel } Typical composition	These grades have a very high YS (> 620 N/mm²), and a UTS > 800 N/mm², together with an elongation greater than 40%.

Table 1.2.1 - Major families of stainless steels

The mechanical properties of the principal stainless steel grades available on the market are given in Table 1.2.2, together with their standard designations.

Table 1.2.2 - Mechanical properties of different stainless steels in the annealed condition

European designation (EN 10088-2)		AISI (1) or commercial	Mean mechanical properties		
Name	Number	American designation	UTS (2)	0,2% YS (3)	El. (%) (4)
Martensitic stainless steels					
X20Cr13	1.4021		550	340	24
X30Cr13	1.4028	420	600	340	24
X46Cr13	1.4034		650	400	23
Ferritic stainless steels					
X6Cr13	1.4000	410S	480	330	26
X2CrTi12	1.4512	409	410	250	32
X2CrNi12	1.4003		510	370	27
X8Cr17	1.4016	430	500	340	26
X3CrTi17	1.4510	430Ti	450	300	30
X2CrMoTi18-2	1.4521	444	540	380	27
Austenitic stainless steels					
X10CrNi18-8	1.4310	301	740	320	50
X5CrNi18-10	1.4301	304	630	300	52
X2CrNi18-9	1.4307	304L	620	310	50
X2CrNi19-11	1.4306	304L	600	300	50
X6CrNiTi18-10	1.4541	321	610	280	48
X4CrNi18-12	1.4303	305	580	250	52
Molybdenum-containing austenitic stainless steels					
X5CrNiMo17-12-2	1.4401	316	620	340	48
X2CrNiMo17-12-2	1.4404	316L	610	310	45
X6CrNiMo17-12-2	1.4571	316Ti	610	310	47
X1NiCrMoCu25-20-5	1.4539	904L	650	340	40
Duplex austenitic-ferritic stainless steel					
X2CrNiMo22-5-3	1.4462		840	620	30
Heat resisting austenitic stainless steels (EN 10095)					
X15CrNiSi20-12	1.4828		620	310	50
X12CrNi23-13	1.4833	309S	630	330	45
X8CrNi25-21	1.4845	310S	600	300	42

(1) AISI: American Iron and Steel Institute.
(2) UTS: Ultimate Tensile Strength (N/mm^2).
(3) 0.2% YS: Yield Strength 0.2% offset (N/mm^2).
(4) El. (%): Elongation in 80 mm (%).

Principal applications

The most significant applications for the different grades are given below.

Austenitic stainless steels (0.015 – 0.1% C, 17 – 20% Cr, 7 – 25% Ni, 0 – 4% Mo)

The principal applications concern the storage and treatment of foodstuffs, collective catering and hospital equipment. They also constitute the standard materials for chemical engineering equipment and are widely employed for domestic utensils and appliances.

Ferritic stainless steels (0.02 – 0.06% C, 11 – 29% Cr)

The 11% Cr steels are used in automotive exhaust systems, where the atmospheres are moderately aggressive. The principal application of the 17% Cr grades is for the manufacture of domestic implements and appliances. The 29% Cr alloys have exceptional corrosion resistance and are essentially used in contact with sea water.

Duplex austenitic-ferritic stainless steels

The most commonly used duplex grade is the 0.02% C – 22% Cr – 5.5% Ni - 3% Mo alloy, whose standard European designation is X2CrNiMo22-5-3 / 1.4462. Its principal applications concern equipment for papermaking and chemical and offshore engineering.

Martensitic stainless steels (C > 0.1%, 12 – 14% Cr)

Like many plain carbon steels, these alloys are used in the quenched and tempered condition, giving the end product a hardness perfectly adapted to the intended utilization. Depending on the grade considered, the principal applications are for cutlery and surgical instruments.

1.3 Choice of a stainless steel grade

Various criteria of stainless steel selection

The choice of a stainless steel grade is usually based on a number of criteria, including the fulfillment of functional requirements, fabricability, and cost effectiveness for the intended application. The following fundamental factors are favorable for stainless steels in general:

– *Corrosion resistance and general durability:*
  Stainless steels have excellent corrosion resistance in a wide variety of media.

– *High mechanical strength at high temperatures and remarkable strength and ductility at low temperatures:*
  Stainless steels have excellent strength, ductility and toughness over a very wide temperature range, from cryogenic temperatures to more than 1000 °C.

– *Attractive appearance:*
  Stainless steel is a modern material whose long lasting appearance is one of its essential features.

– *Ease of implementation:*
  Stainless steels can be readily formed (drawing, contour forming, etc.) and joined (welding, adhesive bonding, etc.).

– *Stainless steels do not alter the taste of foodstuffs:*
  This is an important property for the agriculture, food and beverage processing industries.

– *Stainless steels are easy to clean, disinfect and sterilize:*
  and have perfect resistance to the reagents used for these purposes (e.g. high pressure steam for sterilization).

– *Low overall costs (ownership or life cycle cost):*
  When the equipment purchase price plus its lifetime maintenance costs are considered, stainless steel is a cost-effective material.

– *Recyclability:*
  Stainless steel can be 100% recycled, and is effectively recycled to produce the same quality level as in the initial material.

The combination of the above criteria has led to the widespread use of stainless steel in the agriculture, food and beverage processing industries, including the following applications:
– fruit juices,
– beer (processing and distribution),
– chocolate,
– tomatoes (harvesting and processing),
– fish (handling and processing),
– cheese (from milking to final conditioning),
– wine (grape harvesting, vinification, storage).

They are also extensively used in transport equipment (railroad cars, wagons, truck tanks, refrigerated containers, bus bodies, etc.), in chemical and petrochemical engineering, in the oil industry, in electronics (non-magnetic components for electron guns, glass-metal fixing pins) and in the building industry (curtain walling, elevator cages, escalators, roofs, fume ducts, street furnishings, etc.). This list is by no means exhaustive and stainless steels are used for a large number of everyday objects, of which coinage is a good example.

On the basis of the above fundamental criteria, the following list of applications and appropriate steel grades has been drawn up, classified according to the five major families of stainless steels already described (Chapter 2 and annex I).

In which specific cases should a stainless steel be chosen (in accordance with the five families)

Austenitic stainless steels (0.015 - 0.1% C, 17 - 20% Cr, 7 - 25% Ni, 0 - 4% Mo)

- *Milk storage tanks*
  - X5CrNi18-10 / 1.4301
- *White wine storage tanks*
  - X2CrNiMo17-12-2 / 1.4404
- *Beer kegs*
  - X5CrNi18-10 / 1.4301
- *Equipment for collective catering, hospitals, foodstuff handling, etc.*
  - X5CrNi18-10 / 1.4301
  - X2CrNiMo17-12-2 / 1.4404
  - X2CrNi18-9 / 1.4307
- *Sink bowls and complete sink unit*
  - X5CrNi18-10 / 1.4301
- *Dishwasher tubs and door linings*
  - X5CrNi18-10 / 1.4301
- *Cooking utensils*
  - X5CrNi18-10 / 1.4301
- *Cutlery and dishes*
  - X5CrNi18-10 / 1.4301
- *Bus and coach bodies*
  - X5CrNi18-10 / 1.4301
- *Fume ducts*
  - X5CrNi18-10 / 1.4301
  - X2CrNiMo17-12-2 / 1.4404
  - X1NiCrMoCu25-20-5 / 1.4539 depending on the technology (rigid, flexible, single or double wall, with or without condensation, type of fuel, etc.).
- *Hot water tanks*
  - X2CrNiMo17-12-2 / 1.4404
  - X6CrNiMoTi17-12-2 / 1.4571

Ferritic stainless steels (0.02 - 0.06% C, 11 - 29% Cr)

- *Domestic appliances: washing machine and drier drums, dishwasher tubs*
  - X6Cr17 / 1.4016
- *Sink bowls and drainboards*
  - X6Cr17 / 1.4016
  - X3CrTi17 / 1.4510
- *Cutlery, dishes, pan lids*
  - X6Cr17 / 1.4016
- *Automobile hose clamps*
  - X6Cr17 / 1.4016
- *Decorative automobile trimmings*
  - X6Cr17 / 1.4016
  - X6CrMo17-1 / 1.4113
  - X6CrMoNb17-1 / 1.4526
- *Washing machine tubs*
  - X3CrTi17 / 1.4510
- *Hot water tanks*
  - X2CrTi17 / 1.4520
  - X2CrMoTi18-2 / 1.4521
- *Automotive exhaust systems*
  - X2CrTi12 / 1.4512
  - X2CrTiNb18 / 1.4509
- *Drier-superheater tubes (electric power stations)*
  - X3CrTi17 / 1.4510
- *Evaporator and reheater tubing and boilers for sugar refineries*
  - X3CrTi17 / 1.4510
- *Fume ducts*
  - X2CrMoTi18-2 / 1.4521
  - X2CrMoTi29-4 / 1.4592
- *Tubing for seawater desalination plants*
  - X2CrMoTi29-4 / 1.4592
- *Conveyor belt chains*
  - X6CrNi17-1 / 1.4017
- *Structural elements, container frames, wagons, hoppers, bus and coach bodies*
  - X2CrNi12 / 1.4003
- *Coinage*
  - X6Cr17 / 1.4016 with low carbon content

Duplex austenitic – ferritic stainless steels

The most commonly used duplex grade is the 0.02% C – 22% Cr – 5,5% Ni– 3% Mo alloy, whose standard European designation is X2CrNiMo22-5-3. Its principal applications are as follows:

- *Chemical engineering*
  - heat exchangers for PVC plants
  - equipment for handling organic acids
  - tanks and tubing
- *Papermaking*
  - pressure vessels
  - pre-impregnators
  - boilers
  - kraft pulp digesters
- *Offshore engineering*
  - seamed spiral tubing
  - fire resistant walls
- *Miscellaneous*
  - plates for electrostatic precipitators

Martensitic stainless steels
(C > 0.1%, 12 – 14% Cr)

Like many plain carbon steels, these alloys are used in the quenched and tempered condition, giving the end product a hardness perfectly adapted to the intended utilization. Depending on the grade considered, the principal applications are as follows:

- *Knife blades*
  - X20Cr13 / 1.4021
  - X30Cr13 / 1.4028
  - X46Cr13 / 1.4034
- *Shear blades for the paper industry*
  - X30Cr13 / 1.4028
- *Compressor membranes, springs*
  - X20Cr13 / 1.4021
- *Surgical instruments*
  - X30Cr13 / 1.4028
  - X46Cr13 / 1.4034

Heat resisting austenitic stainless steels

- *Furnace components, heat exchangers*
  - X12CrNi23-13 / 1.4833
  - X8CrNi25-21 / 1.4845
- *Burners*
  - X12CrNi23-13 / 1.4833
- *Furnace bells*
  - X15CrNiSi20-12 / 1.4828
- *Automobile exhaust manifolds*
  - X15CrNiSi20-12 / 1.4828

1.4 Heat treatment

Martensitic stainless steels

The martensitic stainless steels generally have chromium contents ranging from 11.5 to 18% and carbon levels between 0.15 and 1.2%. A noteworthy application is for cutlery manufacture. The microstructure of these materials on delivery usually consists of a uniform dispersion of carbides in ferrite, although some thin strip is supplied in the as-quenched condition. Before use, for example in cutlery, quenching and tempering is therefore normally necessary to obtain a fully martensitic structure with no chromium carbides.

In order to develop a completely martensitic structure, it is necessary to heat the metal into the single phase austenite field, above the Ac_3 transformation point, generally of the order of 900 °C, depending on the chromium and carbon contents. For alloys with between 11.5 and 13.5% Cr and carbon contents less than 0.15%, the Ac_3 point is situated at about 920 °C and austenitizing is performed between 950 and 1100 °C. For carbon contents between 0.15 and 0.5% and chromium levels from 12 to 16%, Ac_3 lies between 850 and 900 °C and austenitizing is also carried out in the range from 950 to 1100 °C. For grades containing 0.6 to 1.2% C and 17 to 18% Cr, Ac_3 is between 830 and 860 °C and quenching is performed from temperatures between 1000 and 1050 °C. Finally, there is a fourth category of stainless steels, with less than 0.2% C and from 12 to 18% Cr, and also containing from 1.5 to 5% Ni, whose Ac_3 is between 800 and 900 °C and which are austenitized between 950 and 1000 °C.

The holding time at the austenitizing temperature depends on the thickness, and must be long enough to allow complete solutioning of all chromium carbides. Subsequent cooling down to ambient temperature must be effective in less than one minute. For thin sections, natural or forced air cooling is often sufficient, whereas oil quenching is necessary for thicknesses greater than about 5 mm. If chromium carbides are observed after cooling, either the austenitizing temperature was too low or the holding time too short. The hardness will then be too low, since the carbon content of the martensite is reduced, and the corrosion resistance may also be impaired.

In high carbon grades, the austenite does not transform fully to martensite on cooling to room temperature, and the presence of residual austenite lowers the overall hardness. The transformation can be effectively completed with the aid of a cryogenic treatment at about -80 °C. The thermal shock induced during rapid cooling generates internal stresses which can cause embrittlement. In order to improve the ductility and toughness, a stress relieving treatment is therefore performed, involving heating for a few hours at 150 to 300 °C. It is absolutely essential to avoid the temperature range 400-600 °C, in which chromium carbide precipitation can occur, accompanied by chromium depleted zones which can make the alloy sensitive to intergranular corrosion.

Ferritic stainless steels

In metallurgical terms, the ferritic stainless steels are not all identical, since, while some remain ferritic at all temperatures, the so-called semi-ferritic grades can form up to 30% of austenite at high temperatures, which transforms to martensite on cooling. Furthermore, in non-stabilized alloys, which includes the semi-ferritic grades, holding in the temperature range 900-950 °C followed by slow cooling can lead to the precipitation of chromium carbides and sensitization to intergranular corrosion due to chromium depletion at grain boundaries. The ductility and corrosion resistance of the semi-ferritic alloys can be restored by heat treatment between 750 and 850 °C, for a time which depends on product thickness, a value of one to two minutes per millimeter being recommended. Subsequent cooling, particularly through the temperature range around 475 °C, must be sufficiently rapid to avoid embrittlement. Indeed, at temperatures between 400 and 500 °C, the ferrite matrix splits into two separate body cubic centered (bcc) phases, with respectively high and low chromium contents, the rate of reaction being a maximum at 475 °C. The 11% Cr ferritic grades are virtually insensitive to this phenomenon, which occurs only to a slight extent in 17% Cr alloys, whereas the 25% Cr materials are highly prone to it.

The grades with more than 25% Cr are also susceptible to the formation of the brittle chromium-rich sigma phase between 500 and 800 °C. It can be taken back into solution by heat treatment at 1000 °C for about half an hour, followed by rapid cooling.

The semi-ferritic 17% Cr alloys have a two-phase austenite + ferrite field situated between 850 and 1100 °C. If the alloy has been held in this region, martensite will be present on cooling to room temperature. In fact, the embrittlement of these materials due to martensite is only relative, and is much less detrimental than the presence of chromium carbides at grain boundaries, which not only impair the corrosion resistance, but also promote intergranular fracture at high stresses. Embrittlement of semi-ferritic grades (e.g. X6Cr17/1.4016) due to the precipitation of chromium carbides, nitrides or carbonitrides appears after holding at temperatures above 900-950 °C. This phenomenon can be avoided by ensuring a correctly balanced alloy chemistry. Thus, the interstitial elements, carbon and nitrogen, must be limited to a total content of not more than 0.020%, and must be tied up with titanium, which forms TiN nitrides in the liquid phase during solidification, and/or with niobium, both elements forming carbonitrides in the solid phase.

Another group of alloys which can be included with the ferritic grades includes the dual-phase ferrite-martensite materials, whose high temperature structures contain up to 50% of austenite, and which consist of ferrite and about 10% martensite at ambient temperature. The heat treatment employed for these alloys is designed to form the amount of austenite necessary to produce the required quantity of martensite in the final structure. The cooling rate must be greater than 20 °C/hour to prevent the presence of residual austenite.

Austenitic stainless steels

Solution annealing

The aim of solution annealing is to obtain a fully homogeneous austenitic structure at ambient temperature. Annealing is performed at 1000 to 1150 °C, depending on the grade, with a holding time of the order of one to three minutes per millimeter of thickness, and is followed by very rapid air or water cooling.

"Anti-ferrite" treatment

A certain amount of high temperature delta ferrite can be retained in austenitic stainless steels. This phase is not generally detrimental, but may become embrittled due to the formation of sigma phase between 550 and 900 °C. This residual ferrite can be eliminated by holding for about 36 hours at 1150 °C, followed by slow furnace cooling to 1050 °C, then rapid cooling down to ambient temperature.

Stress relieving treatments

The various processing operations during the manufacture of a component can generate internal stresses which can have a detrimental influence on the service life of the equipment in which it is employed, for example, due to stress corrosion cracking. In order to eliminate or attenuate these residual stresses, two types of stress relieving treatments can be employed:

a) Long holding (10 to 20 minutes per millimeter of thickness) at a temperature between 200 and 400 °C, followed by slow cooling. This treatment has the advantage that it does not cause any phase transformations.
b) For grades not prone to intergranular corrosion, short holding (about 3 minutes per millimeter of thickness) at about 850 °C.

Duplex austenitic-ferritic stainless steels

Solution annealing

For duplex austenitic-ferritic stainless steels, the aim of solution annealing treatments is generally to obtain a mixture of roughly 50% austenite and 50% ferrite at room temperature, without the presence of intermetallic phases or other precipitate particles. It is essential to avoid the precipitation of intermetallic phases during cooling, particularly since the ferrite in duplex grades is also sensitive to the 475 °C embrittlement phenomenon. Residence times in the range 950 to 700 °C must be as short as possible in order to limit the risk of sigma phase formation. In molybdenum-containing grades, the dangerous zone extends up to 1050 °C. The recommended annealing temperature is therefore about 1050 °C for molybdenum-free alloys and 1100 °C when this element is present. Bearing this in mind, the temperature must be chosen in the range 1000-1150 °C, according to the required volume fractions of austenite and ferrite.

Post-weld heat treatment

Since duplex austenitic-ferritic stainless steels are not sensitive to intergranular corrosion, from this point of view they do not really require post-weld heat treatment. However, the welding operation, particularly in the case of a single pass process without filler metal, destroys the balance between austenite and ferrite in the weldment, where it is common to find ferrite contents of 90% and more. In order to restore a more balanced phase mixture, it is recommended to perform a solution annealing treatment as described under the section “solution annealing”.

1.5 Commercially Available Stainless Steel Products

A major distinction is generally made between flat (about 85% world stainless steel consumption) and long products (about 15% world stainless steel consumption) (Table 1.5.1 and 1.5.2).

Photo 3: Slitting line in action

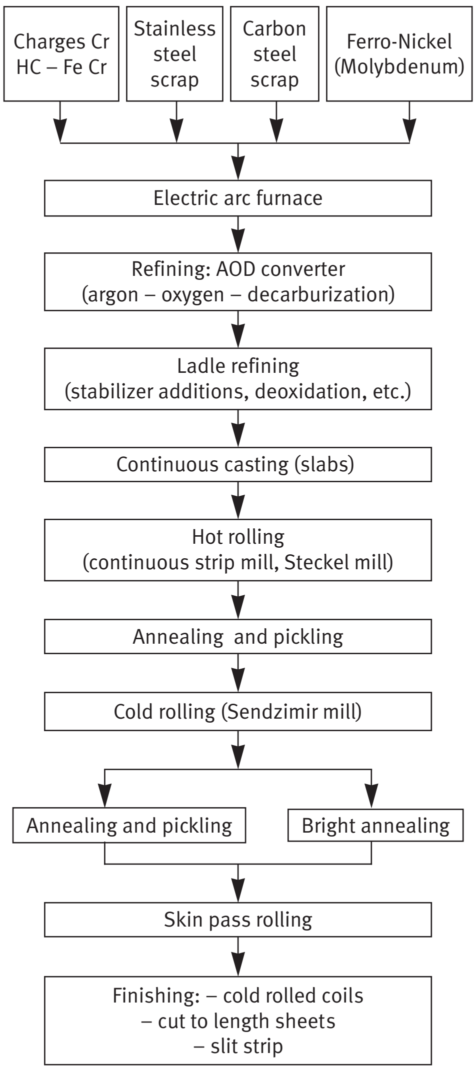


Table 1.5.1 - Principal manufacturing route for coiled stainless steel strip products

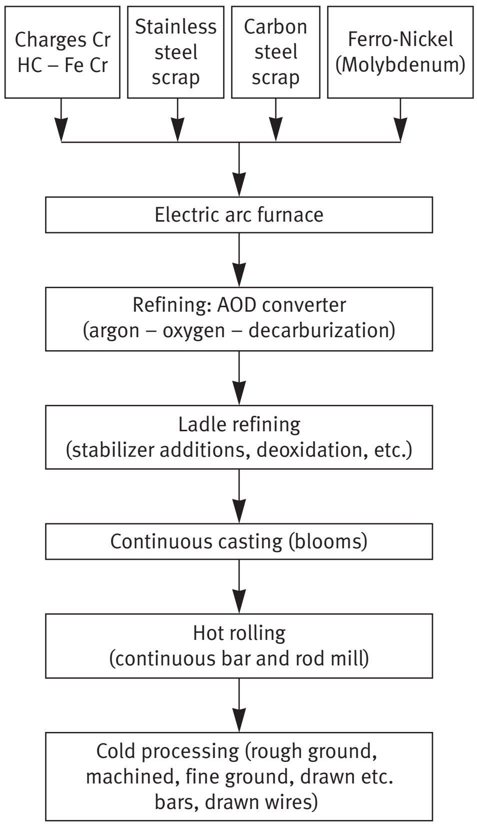


Table 1.5.2 - Principal manufacturing route for stainless steel long products

Flat products

Flat products represent about 85% of world stainless steel consumption. They can be subdivided into:

- Coiled strip, including:
  - hot rolled strip, in thicknesses from 2.0 to 13.0 mm,
  - cold rolled strip, in thicknesses from 0.3 to 8.0 mm, together with extra-thin strip with thicknesses down to 50 µm, which can be supplied in widths up to 1000 mm.

The most common strip width is 1250 mm, although widths up to 1500 mm, and exceptionally 2000 mm are available for some thicknesses.

- Sheets and plates, with thicknesses up to 150 mm and widths up to about 4000 mm.

The largest volume corresponds to cold rolled strip, which alone represents more than 75% of total flat product usage.

These products are employed either in the annealed (ferritics) or solution treated and quenched (austenitics, duplex grades) condition, or in the cold-worked state, in order to obtain higher yield and tensile strengths. Indeed, the ferritic grades X6Cr17 / 1.4016 and X6CrMo17-1 / 1.4113 are frequently used in the cold worked condition, and this is even more common for the austenitic alloys X10CrNi18-8 / 1.4310, X5CrNi18-10 / 1.4301 and X2CrNiN18-7 / 1.4318, whose mechanical strength can be considerably increased by controlled cold work.

Table 1.5.3 gives the mechanical properties obtained in the cold worked condition for the most representative ferritic and austenitic grades.

These different strength levels are obtained by appropriate amounts of cold rolling. The class C850 corresponds roughly to quarter hard temper, the class C1000 to half hard, class C1150 to threequarters hard and class C1300 to full hard, i.e. the maximum allowable cold reduction.

These flat products can be delivered with a wide variety of surface conditions, the principal ones being:

- N°. 1 finish, corresponding to the surface condition of a hot rolled strip after annealing and pickling (1D condition).
- N°. 2 finish, corresponding to the surface condition of a cold rolled strip after annealing and pickling (2D condition).

Standard designation EN 10088-2	UTS (N/mm²) for different degrees of cold work				
	C700	C850	C1000	C1150	C1300
X6Cr17 / 1.4016	700/850	850/1000			
X6CrMo17-1 / 1.41133	700/850	850/1000			
X10CrNi18-8 / 1.4310		850/1000	1000/1150	1150/1300	1300/1500
X5CrNi18-10 / 1.4301		850/1000	1000/1150	1150/1300	1300/1500
X2CrNiN18-7 / 1.4318		850/1000	1000/1150		

Table 1.5.3 - Ultimate Tensile Strength (UTS) of stainless steels in different "temper" (cold worked) categories

- N°. 2B finish corresponds to condition 2D after “skin-pass” rolling, to decrease the roughness and thus enhance the brightness (2B condition).
- The bright annealed finish is obtained by performing the final annealing treatment in a controlled atmosphere (a nitrogen-hydrogen mixture or pure hydrogen). This gives a very smooth surface whose brightness is enhanced by skin-pass rolling (2R condition).

In addition to the above surface conditions, a wide variety of other finishes exist, such as polished (2G conditions), brushed satin (2J conditions) and etched (leather, canvas, etc. - 2M conditions) (fig. 1.5.1).

HOT PROCESSING

COLD PROCESSING

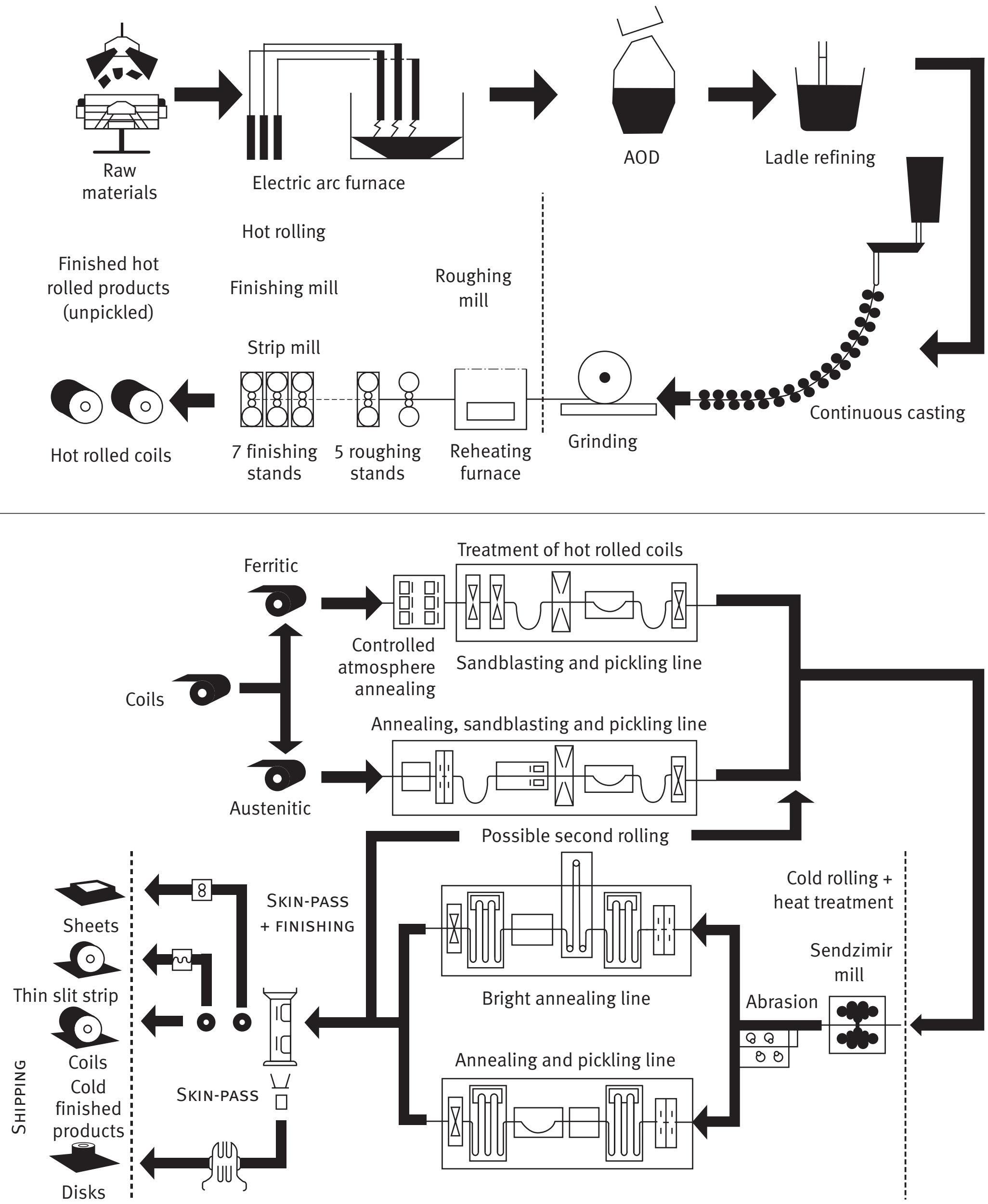


Fig. 1.5.1 - Manufacturing route for stainless steel flat products

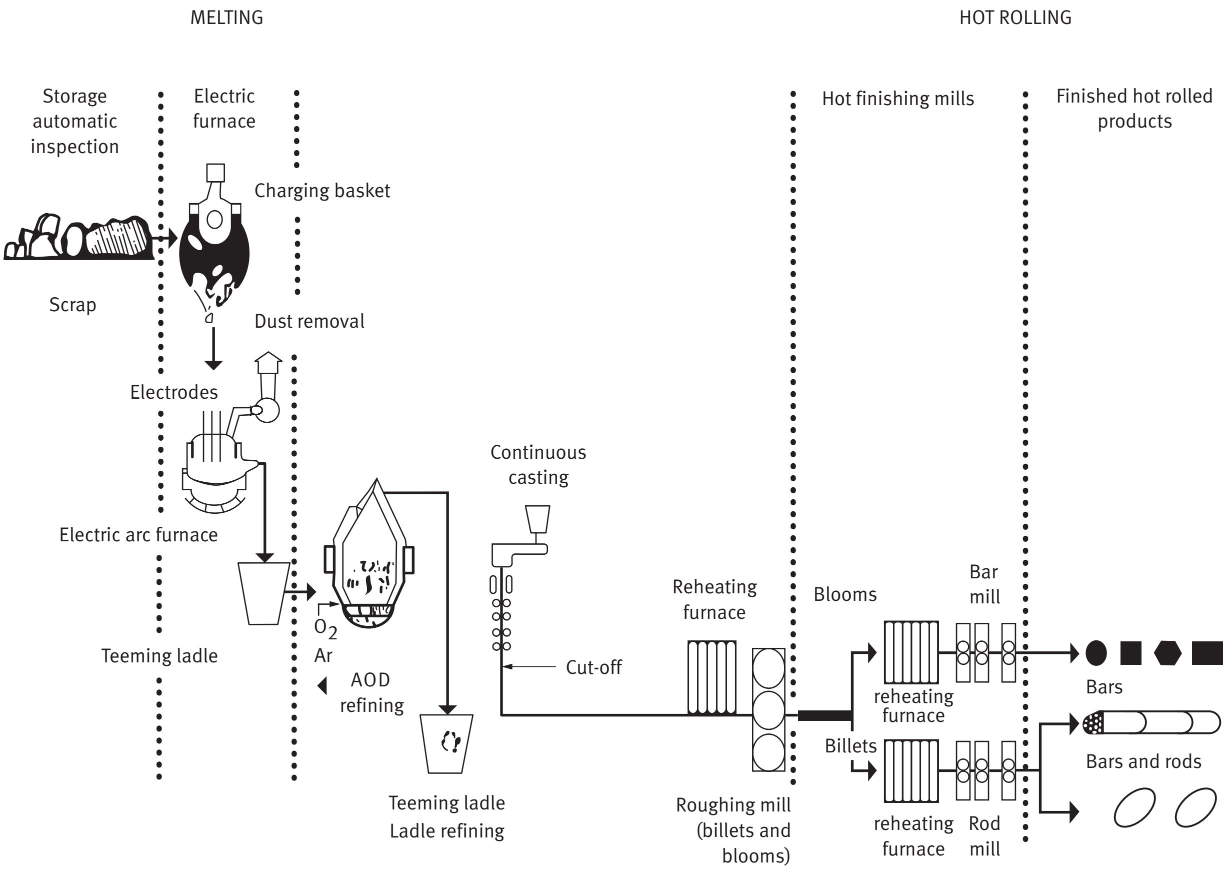
Long products

Long products represent about 15% of world stainless steel consumption. They consist typically of bars, wires, standard sections (round, square, rectangular) and special sections (angle irons, U, T and I beams). These products can be delivered in the hot rolled condition, possibly after different thermal and mechanical treatments, such as descaling, peeling, etc., or after cold processing (drawn, machined, ground, polished, etc.)

In the case of bar and rod, the most common diameters range from 2 to 45 mm. Products with diameters less than or equal to 10 mm can be given a so-called decorative polish. Wire and wire rod with diameters from 2 to 16 mm are frequently used for cold heading (fasteners). The building industry uses wires with diameters between 2 and 5 mm for decorative purposes, while slate hooks are made from 2.4 to 2.7 mm diameter wire.

The manufacturing route for stainless steel long products is illustrated in figure 1.5.2.

Fig. 1.5.2 - Manufacturing route for stainless steel long products



Tubes

The largest category of tubes corresponds to those produced by the continuous welding of strip. The major applications are for the transport of fluid ("corrosion" tubing), for decorative purposes ("decorative" tubing) and as structural elements.

Corrosion tubing is generally continuously welded using the TIG (tungsten inert gas) process, or the plasma or laser processes for thicker gages. These tubes are practically always circular in section.

Decorative tubing, on the other hand, can have either circular, square or rectangular sections. The tubes are welded either by one of the three processes mentioned above or by the high frequency induction technique. After welding, they are generally polished.

A very wide range of standardized dimensions are available, the commonest ones being:

- for round sections: 10 to 168.3 mm outside diameter, 0.5 to 2.0 mm thickness;
- for square sections: 12 to 80 mm side length, 1.0 to 2.0 mm thickness;
- for rectangular sections: large side length 20 to 100 mm, small side length 6 to 40 mm, 1.0 to 2.0 mm thickness.

2 Working with stainless steels

2.1 Cutting – thermal cutting

The term "cutting" is used here to describe all the different methods employed to obtain sheets or blanks for subsequent forming and/or joining (e.g. by welding) to produce a more complex structure. Cutting can be performed either mechanically, by techniques such as shearing, punching, nibbling, sawing, etc., or thermally, using a plasma torch or a laser beam, for example.

Photo 4: Hydraulic guillotine shear

Shearing

Straight-blade shearing

The capacity of straight-blade shears is generally given for mild steel. Since larger shearing forces are necessary for stainless steels, particularly the austenitic grades (Fe-Cr-Ni alloys), the maximum permissible thickness for a given machine is about 70% of that for mild steel. For example, a straight-blade shear capable of cutting 5 mm thick mild steel sheet will be limited to thicknesses not greater than 3.5 mm in the case of stainless steels (fig. 2.1.1).

The clearance between blades must be about 4 to 7% of the sheet thickness, with a tolerance of ± 0.01 mm. When shearing is to be performed close to the edge of a sheet, this rule must be applied very strictly. Greater tolerance is possible for cutting in mid-sheet. For 1.5 mm thick sheet, the recommended clearance is 0.07 mm. For thicknesses larger than 1.5 mm, a clearance of the order of 0.1 mm represents a good compromise. The cutting or rake angle between the plane of the sheet and the blade end face can vary from 0° 30’ to 2°, a value of 1° 30’ being frequently employed.

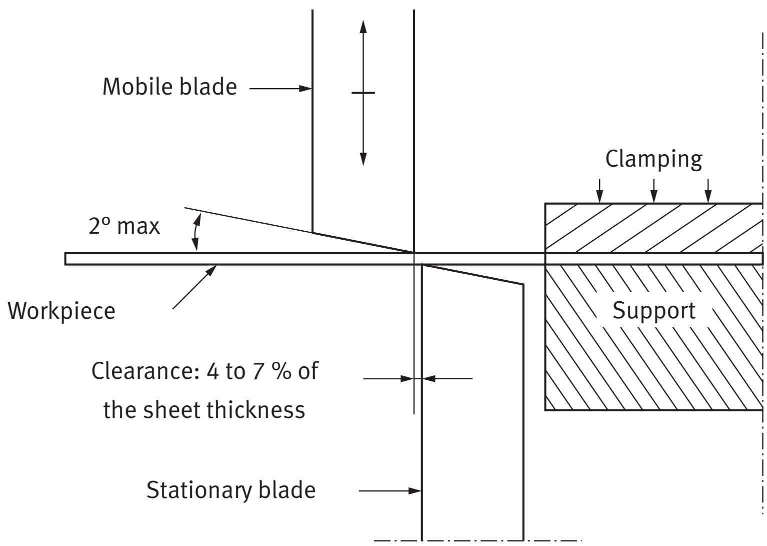


Fig. 2.1.1 - Mechanics of straight-blade shearing

The materials recommended for the shear blades are either quenched tool steels or chromium alloy steels. In order to increase their life between sharpening operations, they should be slightly lubricated with paraffin wax or a high viscosity oil.
In common with all operations involving the contact between a tool and stainless steel, it is imperative to use blades dedicated exclusively to the cutting of these materials, in order to avoid all risk of contamination, particularly by iron-rich particles.

When sheet is sheared to obtain narrow strips, their width must be at least 30 times the thickness. Thus, for a 1 mm thick sheet, the minimum permissible strip width will be 30 mm.

With regard to the shearing equipment, care must be taken to prevent the blankholder from damaging the sheet surface (scratches, indentations, etc.). Particularly in the case of thin sheets, the clamp jaws should be coated with elastomer.

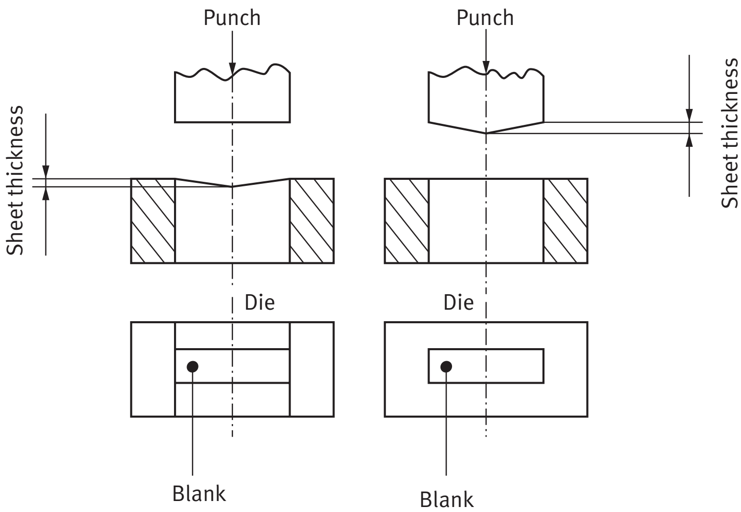
After shearing, examination of the cut edge is a good means of inspection. If the clearance is correct, the smooth upper part of the cut, corresponding to the blade penetration, should represent about 40% of the thickness, the lower fractured or torn portion making up the remaining 60%. If the clearance is too small, the fractured zone will cover the whole of the edge area, while if it is too large, the metal flows between the two blades, leading to a burr, with excessive local strain.

Slitting

Slitting consists in cutting coiled stock into a number of narrower strips. A typical application of this process is the production of strip for the manufacture of welded tubes (the strip is formed into a multiple roll forming system and the edges are welded together longitudinally). In order to obtain a satisfactory cut, the horizontal clearance and vertical overlap of the circular slitting blades must be appropriately adjusted. A cold worked austenitic stainless steel or an as-quenched martensitic grade requires a small ratio between the vertical overlap and the strip thickness. An average value for the horizontal clearance is 5% of the strip thickness. Depending on the stainless steel grade and the strip thickness, slitting speeds vary from 60 to 200 m/min. A sharp edge must be maintained on the circular blades to prevent burr formation at the cut edges of the strip. In order to increase blade life, it is recommended to use a soluble oil or paraffin-based lubricant. The materials recommended for the blades are the same as for straight blade shearing.

Blanking

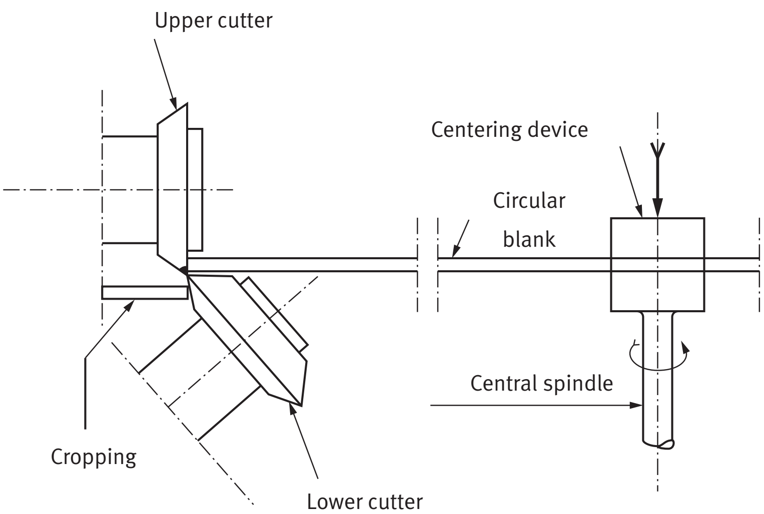
Fig. 2.1.2 - Press punching of rectangular blanks



Press punching

The blanking of stainless steels requires more powerful presses than for mild steels. In order to facilitate cutting, either the punch or the die can be machined at an oblique angle to create a difference in axial length between the center and the edge approximately equal to the sheet thickness. The clearance between the punch and the die must be between 5 and 10% of the workpiece thickness (fig. 2.1.2).

Fig. 2.1.3 - Rotary shearing



Rotary shearing

As in the case of slitting, the rotary cutters must overlap. This process is used for cutting out large diameter circular blanks for tank bottoms or large stampings. The maximum diameter that can be produced is about 2 m, for thicknesses up to 4 mm. The clearance usually employed is of the same order as for slitting. For the production of circular shapes, the cutting point is guided by a centering device placed in the middle of the blank. The imprint left by the clamping of this centering system must be subsequently eliminated, or better, avoided by using a suction pad (fig. 2.1.3).

Nibbling

Nibbling is a mechanical cutting technique in which material is removed along a path whose width is determined by that of the tooling. The latter is composed of a reciprocating punch which moves in and out of a fixed die, rejecting a crescent-shaped cropping at each stroke. In fact, nibbling is a repetitive punching process, in which the pitch between successive strokes is adjusted as a function of the sheet thickness. A precise cutting path can be followed by using a template guide or a numerical control system. The edges of the cut blank show the marks of the successive punch strokes, which are generally removed by fine grinding (fig. 2.1.4).

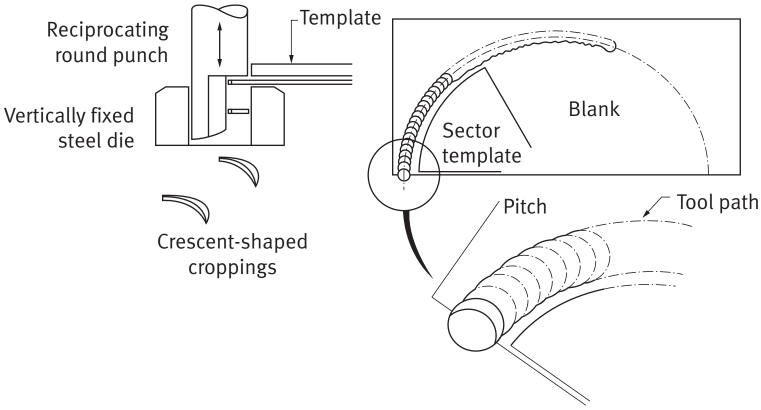


Fig. 2.1.4 - Nibbling

Piercing and perforating

Piercing and perforating are commonly used for cutting holes in sheet, the minimum diameter being twice the sheet thickness, with a minimum distance between adjacent holes equal to half the diameter. The forces necessary to pierce stainless steels are significantly higher than those for mild steel and are approximately in the ratio of the respective ultimate tensile strengths. In addition to the type of steel, these forces also depend on the effective clearance between the punch and die, on the number of holes punched simultaneously, and on the punching speed (fig. 2.1.5).

The clearance C between the punch and the die is the difference between their diameters, respectively d and D, and is therefore given by $C = D - d$. For routine work, the clearance is defined by the relation $C = 0.12\,t$, where t is the workpiece thickness, while for "precision" piercing, a smaller clearance must be used, corresponding to $C = 0.07\,t$. Pierced holes always show a certain degree of conicity, which increases with the sheet thickness.

The lubricant must be chosen not only to facilitate cutting, but also to prevent the slug from sticking to the tooling.

Lever-operated manual piercing machines are limited to thicknesses of 2 mm and have very low productivity. Mechanical piercing presses are often equipped with quill punches, generally with a guide bushing. Numerically controlled piercing machines offer considerably improved productivity and ensure excellent precision in hole positioning (of the order of ± 0.03 mm). The punch relief angle is a maximum of 3°.

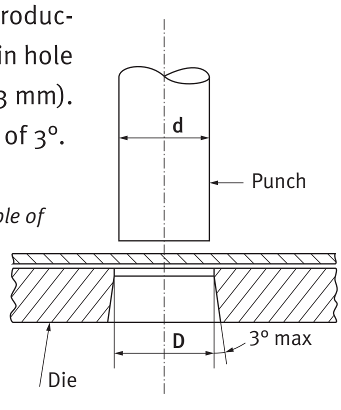


Fig. 2.1.5 - Principle of piercing

Sawing

Manual sawing

Stainless steels can be readily cut with a hacksaw. Contact between the blade and the metal must be during the push stroke, and it is recommended to lift the saw or lighten the pressure during the return stroke to avoid work hardening. The maximum rate is of the order of 50 strokes per minute for blades with between 7 and 12 teeth per centimeter.

Power hack sawing

Power hack saws have reciprocating vertical blades. For stainless steels, short fine-toothed blades are employed. The maximum sheet thickness which can be cut in this way is about 2.0 mm.

Milling cutter sawing

This technique is used for precision cutting, particularly of shaped sections and tubes. The tool is a milling cutter a few millimeters thick. In order to enable cutting at different angles, the toolholder must have a variable orientation. The surface of stainless steel sections must be protected to prevent them from being damaged by the clamping system. In order to avoid the deformation of thin sections, wooden cores of appropriate shape should be placed inside them. The productivity of the process can be increased if the profile of the cut enables several sections or tubes to be mounted together.

Abrasive disk cutting

This technique is mainly employed for field cutting operations, and can only be used for short cuts. The pressure exerted by the disk should be limited to minimize heating and avoid oxidizing the workpiece. If this is not possible, a local pickling and passivation treatment must be performed along the edges of the cut.

Band sawing

Band sawing is the most common cutting technique and is well adapted for straight cuts in metal thicknesses from 0.8 to 8 mm. Depending on the thickness and the grade of stainless steel, the band speed varies from 15 to 40 m/min. The highest speeds are used only for thin gage sheet, the speeds for thicknesses greater than 1.5 mm being limited to the range 15–30 m/min. Use of a lubricant is not necessary, but compressed air must be blown permanently onto the cutting zone to eliminate swarf and prevent excessive heating. In order to increase productivity, thin blanks can be stacked together and cut simultaneously.

Bandsaw cutting is also well adapted to the cutting of bars, giving a higher productivity than with a reciprocating saw. In this case, the band speed can range from 30 m/min for the common austenitic alloy X5CrNi18-10/1.4301 to 40 m/min for the free-machining austenitic grade X10CrNiS18-09/1.4305, and up to 45 m/min for the free-machining ferritic grade X10CrS17/1.4104.

Water jet cutting

In this method, a high pressure water jet (2000 to 5000 bars) containing 0.2 to 0.5 mm abrasive particles of garnet or corundum is projected through a calibrated nozzle perpendicular to the surface of the workpiece, and is displaced laterally at a speed of the order of 20 cm/min. The water jet has a small diameter, and due to its high velocity, two to three times the speed of sound, the resulting cut is of excellent quality. The process can be readily automated and its flexibility makes it well suited to small series cutting operations. When used for stainless steel sheet, it is recommended to cut stacks about 10 mm thick in order to improve productivity, since the cutting speed is not proportional to the thickness.

Thermal cutting

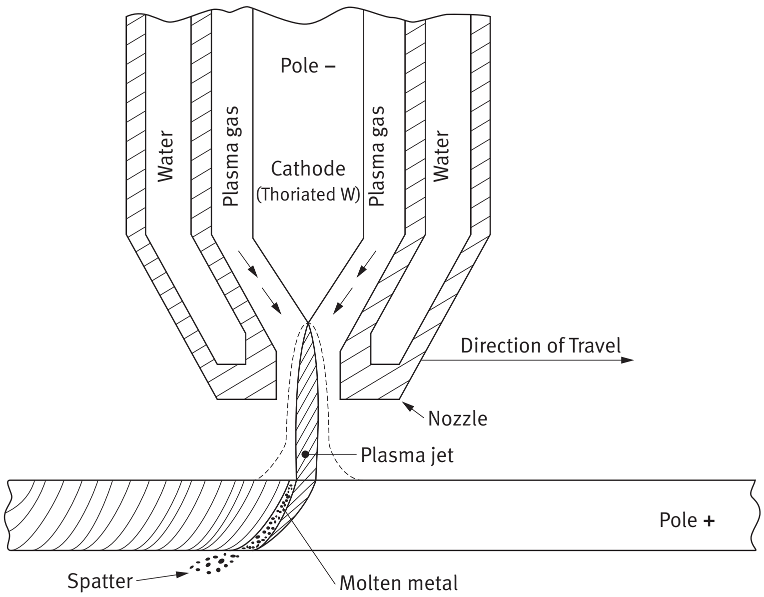
Oxygen-acetylene torch cutting

This process is mentioned only for the sake of completeness, being poorly adapted to the cutting of stainless steels, since it produces considerable oxidation and a large heat affected zone. However, it may sometimes represent an emergency solution. In contrast, powder-assisted oxyfuel cutting is commonly used in steelworks for continuously cast stainless steel slabs, typically about 200 mm thick. In this case, surface oxidation and metallurgical transformations in the heat affected zone are not important.

Plasma-arc cutting

In this technique, the metal is melted locally due to the very high temperature (10000 to 20000 °C) of a confined plasma jet (fig. 2.1.6).

Fig. 2.1.6 - Principle of plasma – arc cutting



The plasma is a strongly ionized gas, the most common sources being argon, argon-hydrogen mixtures, nitrogen, and compressed air. Depending on the gas employed and the type of stainless steel, the degree of oxidation and edge contamination can vary. Simple grinding to a depth of about 0.5 mm is generally sufficient to remove the heat affected zone. When cutting is performed under water, oxidation is reduced and significantly higher speeds are possible. For 3 mm thick austenitic stainless steel sheets, the typical cutting speed is about 3.5 m/min. Compared to the mechanical cutting processes, with the exception of nibbling, the metal loss is higher. Moreover, the cut is not perpendicular, but has a slight relief angle, whose elimination requires further grinding in addition to that necessary to remove the heat affected zone.

Laser beam cutting

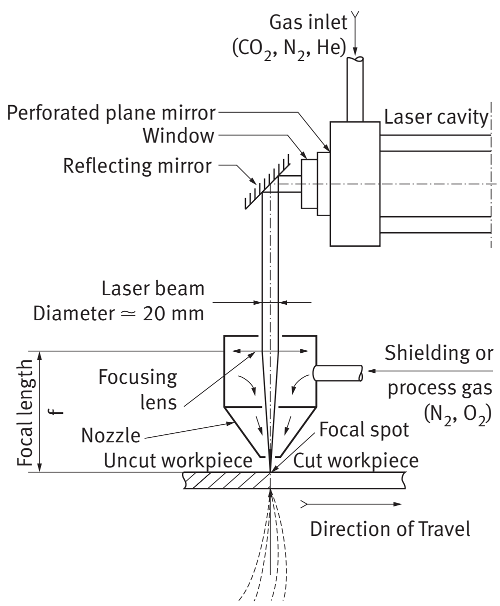


Fig. 2.1.7 - Principle of CO_2 laser beam cutting.

A laser is a device which produces an intense beam of light (LASER = Light Amplification by Stimulated Emission of Radiation). Like in the case of welding, two types of sources are employed for cutting, namely CO_2 lasers, in which the emitting medium is a CO_2–N_2–He mixture, and YAG lasers (yttrium-aluminum garnet). Laser beam cutting is performed either in the continuous emission mode, which allows high speeds to be attained, or in the pulsed mode, which limits the width of the heat affected zones. With CO_2 lasers (fig. 2.1.7), the power levels available range from 0.5 to 3 kW, while YAG lasers are limited to 2 kW, restricting their cutting speeds.

Whatever the laser source, the beam must be transported to the workpiece using either a mirror-based optical guide system (CO_2 lasers) or an optical fiber (YAG lasers). In order to cut the metal, the energy must be concentrated by a focusing system designed to produce a focal spot of diameter d given by $d = \lambda \times f/D$, where λ is the wavelength of the light (10.6 µm for a CO_2 laser), f is the focal length and D is the diameter of the parallel beam before focusing (typically about 20 mm for a CO_2 laser). The depth of field of the focal spot is proportional to $\lambda \times (f/D)^2$. Analysis of these two relations shows that a small focal spot requires a short focal length (f), whereas a long focal distance is required to obtain a large depth of focus. In practice, it is therefore necessary to strike a compromise between either a short (60 mm) or a long (300 mm) focal length. For example, a focal length of about 150 mm gives a focal spot diameter of approximately 0.3 mm and a depth of field slightly less than a millimeter.

Because of their relative performances, it is mainly CO_2 lasers that are used for cutting, the emitting medium being in fact a mixture of 40–80% helium, 15–55% nitrogen and 3.5–7% carbon dioxide. In addition to the "lasing" gas, a shielding or process gas (nitrogen or oxygen) is injected concentrically around the beam through a nozzle and is used to expulse the molten metal. When oxygen is employed, it reacts exothermically with the metal, enabling the use of higher cutting speeds. In order to obtain a good quality cut, the laser beam must be well centered in the nozzle and focused either on the top surface of the workpiece (thin sheet) or at a depth of about a third of the thickness (thick sheet). Table 2.1.1 shows the performances obtained with a 1.5 kW CO_2 laser, used to cut 18% Cr – 9% Ni austenitic stainless steel sheet. When nitrogen is used as the process gas, a high quality cut is obtained, but at the expense of a lower cutting speed.

Finally, it should be pointed out that laser beam cutting is well adapted for cutting, not only flat sheets, but also shaped sections, such as short tubes. Since the laser beam is fixed, a tube section held in the hand of a robot can easily be cut along a complex profile. Obviously, such automatic operations can be envisaged only for sufficiently large series.

For example, this process is employed by certain automobile exhaust manifold manufacturers.

Sheet thickness (mm)	Cutting speed (m/min.)
Process gas = oxygen	
1,0	9,0
2,0	5,0
3,0	3,0
6,0	1,5
Process gas = nitrogen	
1,0	8,0
2,0	3,5
3,0	2,0
6,0	0,5

Table 2.1.1 - Cutting speeds obtained with a 1.5 kW CO_2 laser for 18% Cr-9% austenitic stainless steel sheet

2.2 Machining

Introduction

Among the numerous techniques employed for working stainless steels, machining processes mainly concern long products, although drilling, milling and tapping are frequently performed on flat products. In the latter case, these operations often precede mechanical joining with screws, bolts or rivets. In general, machining is a shaping process in which material is removed with the aid of a cutting tool. The facility with which this can be done depends among other things on the workpiece material. This has given rise to the concept of machinability, applied to a material or family of materials.

In the case of stainless steels, machinability was for a long time considered to be of secondary importance, since these materials were reputed to be difficult to machine, particularly the austenitic grades. However, steelmakers have endeavored to control this property and have succeeded in developing free-machining stainless steel grades, of which two types are presently distinguished:

- resulfurized free-machining grades;
- "controlled oxide- treated" free-machining grades, whose machinability is improved by a controlled distribution and chemical composition of AlSiCa oxide inclusions. The "controlled oxide" treatment can be applied on "low sulphur"grades (up to 0.03% S according to the standards) or on resulfurized grades in order to increase the synergism between the two free-machining methods.

In both cases, close control of the chemical composition and refining process ensures the presence of non-metallic inclusions that promote chip break-up and create a lubricating layer at the tool/chip interface during machining.

Machinability criteria

A large number of factors can affect machinability, but for practical reasons, only those that can be readily observed or measured will be considered, such as chip break-up, tool life, as-machined surface quality (roughness) and power consumption. The productivity will then depend on the cutting conditions and on the ranking of the workpiece material with respect to these different criteria.

Behaviour of the different types of stainless steel

Austenitic stainless steels

These grades have high strain hardening rates, and in the cold worked condition their strength tends to induce rapid tool wear. However, even when heavily cold worked, their ductility is sufficient to cause the formation of long chips which tend to stick to the tool. This can result in the formation of a built-up edge on the tool (sticking phenomenon) that can increase the cutting loads on the tool and as a consequence the risk of tool fracture. High cutting loads are therefore required, leading to rapid tool wear, with the risk of fracture due to damage to the cutting edge. Furthermore, the thermal conductivity of these alloys is about three times lower than for plain carbon steels, leading to a high work-piece/tool interface temperature which reduces tool life. For all these reasons, austenitic grades intended for machining generally have controlled sulfur contents of between 0.15 and 0.35%. However, in the remainder of this chapter, these materials will be considered as “normal” or “regular” grades.

Ferritic stainless steels

Ferritic alloys strain harden much less than the austenitic grades, the Ultimate Tensile Strength increasing by only about 200 N/mm^2 for 50% cold work, compared to more than 1000 N/mm^2 for certain austenitics. However, even though their thermal conductivity is higher and their strain hardening lower than for austenitic alloys, the tendency to form long chips and the risk of sticking remain high. Ferritic stainless steels destined to be machined are therefore almost always resulfurized (cf. the section “Sulfide inclusions”, resulfurized free – machining steels).

Martensitic stainless steels

The strain hardening behaviour and thermal conductivity of these grades are similar to those of low alloy steels, particularly structural steels. However, since they are usually quenched and tempered, they have very high strength, inducing high cutting loads.

Effect of non-metallic inclusions

Sulfide inclusions – resulfurized free-machining steels

The deliberate use of high sulfur contents, typically in the range 0.15 to 0.35%, is a well established technique which produces a spectacular improvement in machinability. The addition of sulfur causes the formation of manganese sulfides whose beneficial effect on machinability has been clearly demonstrated. In contrast, their presence markedly reduces the corrosion resistance, particularly under conditions conductive to pitting. Furthermore, excessive sulfur levels impair both hot workability and weldability, due to an increased risk of hot cracking (mainly for austenitic alloys). For this reason, metallurgists have sought other mechanisms for improving machinability (cf. the section "Oxide inclusions"). High sulfur free-machining versions are available for the three families of stainless steels, austenitic, ferritic and martensitic, and are the most widely used grades for machined components. Their standard designations are as follows:

- X8CrNiS18-9 / 1.4305 and X6CrNiCuS18-9-2 / 1.4570 (austenitics);
- X6CrMoS17 / 1.4105 (ferritic);
- X12CrS13 / 1.4005 and X29CrS13 / 1.4029 (martensitics).

Oxide inclusions

It is well known that hard oxides, such as those rich in alumina (Al_2O_3), silica (SiO_2) or chromite (Cr_2O_3), do not deform and conserve their hardness up to very high temperatures. Inclusions of this type, which are frequently present in standard stainless steels, are therefore highly abrasive and strongly reduce the life of cutting tools. If, on the other hand, the melting and refining practice is modified so as to obtain mixed SiO_2-CaO-Al_2O_3 oxides, which are malleable at high temperatures, then the inclusions are able to deform during machining, becoming heavily elongated in the shear zones of the chip, facilitating its break-up. Moreover, they form a lubricating layer at the tool surface, limiting heating and wear. Alloys of this type have been developed both for long and flat products. For example, compared to the equivalent standard grade, a well-done "controlled oxide" treatment on an X5CrNi18-10/1.4301 leads to a productivity improvement of the order of 25% for turning operations. Finally, unlike the resulfurized grades, with this family of alloys, the improvement in machinability is not obtained at the expense of corrosion resistance, which remains strictly unaffected.

Synergism between the effects of sulfur and malleable oxides

If the two mechanisms for enhancing machinability in stainless steels are combined (sulfur additions and "controlled oxide" treatment), there is found to be a synergism between them that can lead to an increase of the machinability as high as 50% with "controlled oxide" X8CrNiS 18-9/1.4305 compared to the standard grade.

Choice of tools

The appropriate choice of tools is of paramount importance for the machining of stainless steels, and directly determines the productivity. Four different categories of materials can be distinguished:

- Coated and uncoated high speed steels (HSS);
- Coated carbide inserts;
- Cermets;
- Ceramics, silicone-fiber reinforced inserts.

In general, high speed steels are used for drilling and threading, while coated carbide inserts are used for turning and milling (face milling) of stainless steels at higher cutting speed. The coatings most frequently used are made of titanium nitride (TiN), titanium carbonitride {Ti(C,N)} and aluminia oxide (Al_2O_3). Coatings can be applied by two processes:

- Physical Vapor Deposition (PVD) ;
- Chemical Vapor Deposition (CVD).

PVD coatings are applied to the substrate at low temperatures. This process preserves edge strength and permits coating of sharp edges. PVD coatings have a smooth surface that generates less frictional heat, allows lower cutting forces and resists edge build-up that can lead to sticking.

CVD coatings are applied to the substrate at high temperatures. This process causes a diffusion of the coating in the substrate to assure a strong bond. The CVD process also permits deposition of multi-layer coatings that can suppress both crater wear and flank wear, thereby expanding the range of tool application. CVD is currently the only coating process that can efficiently apply aluminia (Al_2O_3), which permits high cutting speeds. The TiN coating, which usually is applied on top, is golden yellow (making the corresponding tools and inserts readily recognizable), while the others are black or grey.

The word cermet is derived from the terms CERamic and METal. Cermets consist mostly carbonitride Ti(C,N) sintered with a metallic phase (Co, Ni, Mo,....) which acts as a binder. Cermets have in the past had a reputation of exhibiting poor thermal and fracture toughnesses.

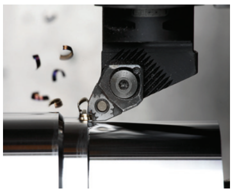


Photo 5: Coated carbide insert used in rough turning

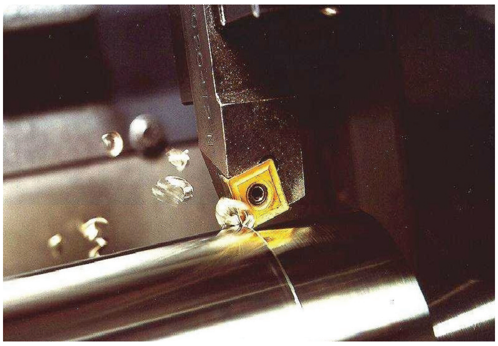


Photo 6: Coated CERMET insert used in finish turning

Recently, new micrograin cermet grades were developed which provide greater thermal toughness and the ability to handle higher cutting speeds (up to 900 m/min). The cermets are principally used for finishing operations. They give an excellent surface, often avoiding the need of finish grinding. They are also ideal to maintain tight tolerances.

Ceramics could previously not be used for stainless steels, but the development of silicon fibre for reinforcement of the inserts have resulted in machining high alloyed stainless steels.

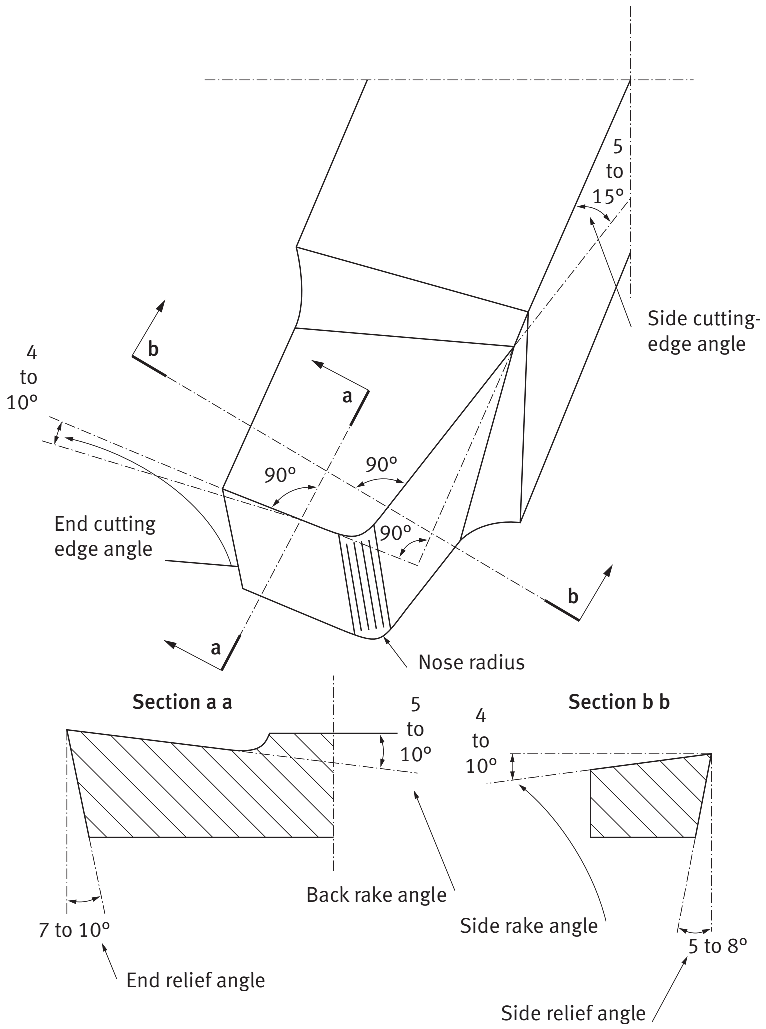


Table 2.2.1 gives typical cutting speeds possible for the machining of stainless steels with different types of tools.

Lathe turning

When turning stainless steels, the workpiece and tool must be held much more rigidly than for plain carbon steels. Depending on the stainless steel and the coated carbide grades, the cutting speed should be in the range 75–750 m/min, with feed rates of 0.1 to 0.3 mm per revolution (mm/rev). The higher speeds can be used with CVD coated carbide tools cutting "resulfurized" and "controlled oxide treated" grades. For rough turning, the cutting speed should be reduced and the feed rate increased, and vice versa for finish machining. Typical tool geometries are given in figure 2.2.1, the exact values depending on the nature of the tool material.

Drilling

Drilling is used in long products, thick sheets and strips, and plates. If it is applied on thin sheets, it is preferable to stack several of them together or to have solid support underneath. Small diameter drilling bits (diameter ⇠ 6 mm) are generally made from high speed steels, intermediate diameter ones from solid (coated) carbides, and larger diameter ones (diameter ⇢ 15 mm) are made from carbide inserts. For long products and thick sheets or plates, the point angle is of the order of 120 to 135°, with a relief angle of about 6°. For thin sheets, in order to reduce surface stresses, the point angle can be increased to 140° and the relief angle reduced to 5° (fig. 2.2.2). The rotational speed of the bit

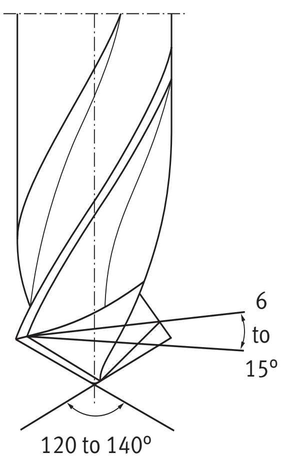


Fig. 2.2.2 - High speed steel drilling bit

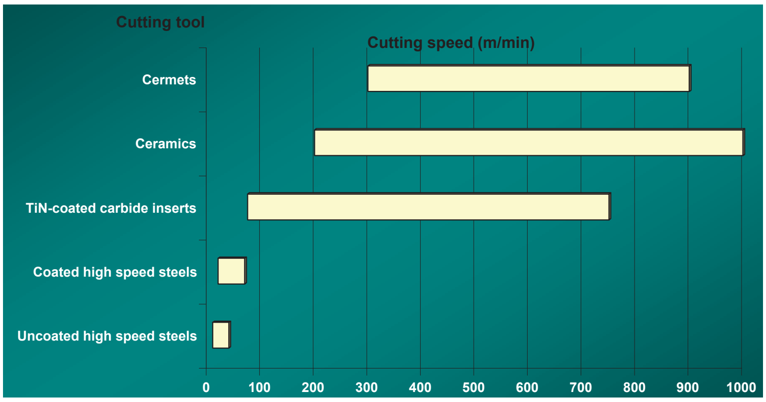


Table 2.2.1 - Range of stainless steel turning speeds possible with different types of tools

(cutting speed) depends on the workpiece material and the type of tool employed, typical values being given in Table 2.2.2.
For the drilling of deep holes, it is recommended to begin with a short bit, and it is important to allow the lubricant to reach the drill tip and to eject the chips by the drill flutes thanks to lubricant channels in the bit and high lubricant pressures (p ⇢ 20 bars). In order to avoid strain hardening the workpiece surface, it is not recommended to use the drill to mark the center point. A self-centering drill or a template should be used for this purpose.
Large diameter holes are produced by trepanning, in which a circular groove is cut, leaving an unmachined core. The tool comprises one, two, or three adjustable cutting edges, and is generally equipped with a centering guide to avoid the need to drill a starting hole.

Boring and reaming

Two types of operation can be used for enlarging previously formed holes, namely boring and reaming. Boring uses simple coated or uncoated carbide cutting tools or inserts. In order to avoid problems of vibration and conicity, the unsupported bar length should be limited to not more than four times its diameter. The cutting speeds employed are significantly lower than for turning, for the same depth of cut. As a general rule, a cutting speed reduction factor of about 0.5 is applied for normal stainless steels and 0.67 to 0.75 for

Table 2.2.2 - Cutting speeds for different stainless steels as a function of drill diameter.

Drill diameter / Workpiece material	3 mm		6 mm		12 mm		18 mm	
	Cutting speed (1) m/min	Feed (1) mm/rev	Cutting speed (1) m/min	Feed (1) mm/rev	Cutting speed (1) m/min	Feed (1) mm/rev	Cutting speed (1) m/min	Feed (1) mm/rev
X5CrNi18-10 / 1.4301	16	0.09	18	0.11	20	0.15	22	0.18
"COT" (2) X5CrNi18-10 / 1.4301	20	0.09	22	0.11	25	0.15	28	0.18
"COT" (2) X8CrNiS18-9 / 1.4305	26	0.17	32	0.20	37	0.24	40	0.30
"COT" (2) X14CrMoS17 / 1.4104	35	0.30	38	0.35	43	0.42	50	0.50
X2CrNiMoN22-5-3 / 1.4462	14	0.09	16	0.11	18	0.15	20	0.18

(1) Cutting parameters to drill over 15 m whithout changing the tool
(2) COT : "Controlled Oxide Treated"

$$\text{Rotational speed (revs/min.)} = \frac{1000 \times \text{Cutting speed (m/min)}}{\pi \times \text{drill diameter (mm)}}$$

free-machining grades. The same feed rates as for turning can be used for a given depth of cut, provided that the unsupported bar length is less than four times its diameter. If this is not the case, a reduction coefficient of 0.67 should be applied to the feed rates employed in turning.

For reaming, high speed steel reamers with helical or straight flutes are usually used for the finishing pass. The rake angle is between 3 and 8°, while the relief angle is about 7°. Hand reamers are generally tapered slightly at the end, while machine reamers also have a chamfer of about 40°. For free-machining stainless steels, the cutting speed is identical to that used for drilling with a high speed steel bit. For normal grades it must be reduced by a factor of 0.67 or even 0.5 compared to that for drilling. The feed rates depend mainly on the reamer diameter. They are generally of the order of 0.10 to 0.20 mm/rev for a diameter of 3 to 4 mm and 0.3 to 0.5 mm/rev for diameters of 8 to 12 mm.

Milling

Because of the generally high cutting forces, powerful machines are necessary, and it is important to eliminate backlash, particularly for climb milling or down milling. As for turning, it is recommended to use coated carbide tools or inserts. For carbide end milling tools, cutting speeds between 90 and 200 m/min are possible for free-machining grades and between 50 and 150 m/min for regular materials. Feed rates vary between 0.012 and 0.125 mm/rev/tooth, depending on the cutter diameter. For face milling equipped with carbide inserts, cutting speeds range from 80 to 400 m/min for free-machining grades and from about 50 to 300 m/min for standard alloys. Feed rates are between 0.05 and 0.20 mm/rev/tooth.

Tapping

Tapping is difficult for austenitic stainless steels, particularly in the case of small diameter holes. The tendency to form filamentary chips can cause tool failure. In order to limit this risk, three-flute taps should be used for small diameters, and four-flute taps for larger diameters. The rake angles are generally between 10 and 15°, with cutting speeds varying from 5 to 30 m/min. Intense lubrication is necessary. The application of a high pressure facilitates chip removal.

Threading

Several methods can be used for machining threads:

- Single point thread cutting on a lathe with an indexable carbide insert or a high speed steel tool.
- Die or tap threading.
- Cylindrical die thread rolling.

For single point threading, the cutting speeds to be used are two thirds those for turning in the case of free-machining grades, and half those for turning for normal grades. For the other threading processes, the cutting speeds with high speed steel tools are beteen 5 and 25 m/min.

2.3 Cold forming

Bending

General aspects

The procedures and equipment used for bending stainless steels are similar to those for mild steel. However, the power necessary to bend austenitic grades (i.e. those containing significant amounts of both chromium and nickel) is 50 to 60% higher than for mild steels. Furthermore, since elastic springback is also greater in austenitic stainless steels, the bending angles must be significantly modified compared to those for mild steels. In the annealed condition, the minimum bending radius is equal to the sheet thickness, while for cold worked materials, the radius of curvature must be increased to about six times the thickness.

Protection of the surfaces of stainless steel sheets

All too often, stainless steel sheets with unprotected surfaces are bent in direct contact with the tooling (punch and die). Friction during bending causes scratching, or in the absence of slip, marks are created due to the imperfections on the tool surfaces. Such practice may be acceptable for invisible structural parts, but is not permissible for decorative components or those intended for food processing or chemical engineering applications. In order to avoid damage to the sheet surfaces, it is recommended to place a sheet of rubber (latex) about 1 mm thick between the tool and the workpiece (fig. 2.3.1). Stainless steel sheets are increasingly supplied with a temporary adhesive protective film, which can be removed after bending, immediately before putting the equipment into service.

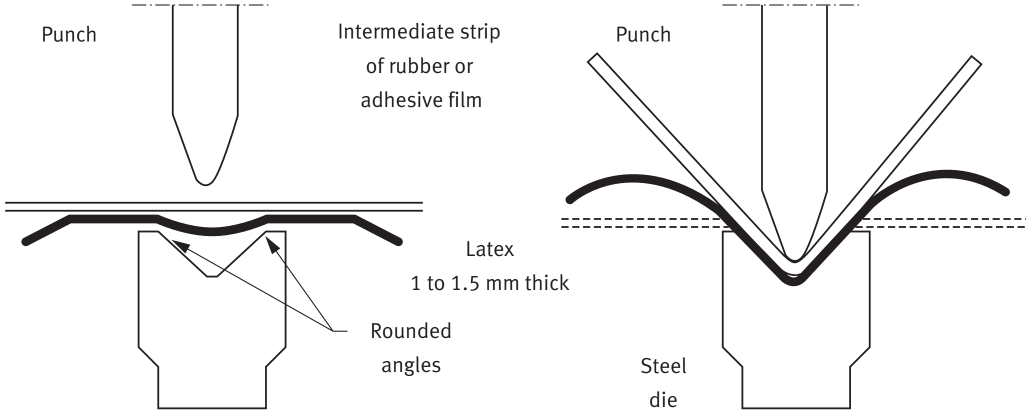


Fig. 2.3.1 - Bending with an intermediate strip of rubber to protect the surface that will be visible in use

Manual bending

Stainless steels can be bent without difficulty, provided that the inside bend radius is not less than the thickness of the sheet concerned.

Mechanical press brake bending

Press brakes are perfectly suited to the bending of stainless steel sheet provided that elementary precautions are taken concerning their cleanness and the surface quality of the tooling. Press brakes are generally limited to useful lengths of 3 m and maximum thickness of the order of 3 mm. They are convenient for producing variable section profiles. In principle, these machines cannot bend to sharp angles, the minimum inside bending radius being about twice the sheet thickness. While certain manual press brakes still exist, most of them are motor driven.

Hydraulic press brake bending

The use of hydraulic presses allows great flexibility and good regularity of bending. This type of machine is appropriate for bending sheets in various grades of stainless steel, for producing profiles, panels and walling. They are routinely employed for bending materials used for building and decorative applications. With tooling in good condition, with correctly protected surfaces, the results obtained are excellent. Four methods are commonly used for the hydraulic press bending of stainless steel sheets:

- open die bending;
- closed die bending;
- closed die bending with angle forging;
- rubber pad bending.

Open die bending

In this process, the sheet is supported on the die at two points beween which the punch nose exerts a pressure (fig. 2.3.2). The punch does not press the sheet against the bottom or sides of the die, but stops at a predetermined distance. Depending on the bending angle, a U-shaped die is often chosen. It is necessary to allow for the elastic springback. With this method, it is possible to bend thick sheets to different angles with the same tooling, but the inside bend radius is always large and cannot be guaranteed.

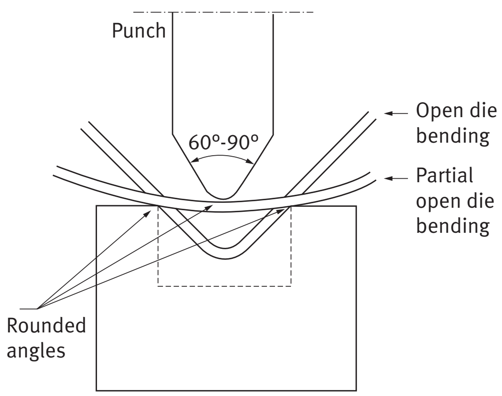


Fig. 2.3.2 - Principle of open die bending

Closed die bending

In this case, the punch or blade presses the sheet against the sides and bottom of the die, but without drawing strain, so that the workpiece adopts the shape of the tool. The inside bend radius is generally equal to the sheet thickness (fig. 2.3.3). This process requires machined tooling adapted to the desired bending angle and radius. For example, in order to allow for elastic springback, a V-shaped die with an angle between 85 and 89° must be used for an effective bend angle of 90°. The opening at the mouth of the V must be 4 to 5 times the sheet thickness for thin gage sheet and 6 to 8 times the thickness for medium gages (about 2 mm).

Closed die bending with angle forging

In this method, bending is performed in two steps, the first of which corresponds to open die bending to obtain the desired angle. In the second step, the punch descends rapidly and sharply strikes the apex of the bend in order to deform it and reduce or eliminate elastic springback, the bending angle being that of the punch. This process can be used to accurately bend stainless steel sheets up to 1.5 mm thick. The inside bending radius can be as small as half the sheet thickness (fig. 2.3.4). However, the blow locally deforms the sheet and can even cause incipient necking, so that the bend is a point of weakness.

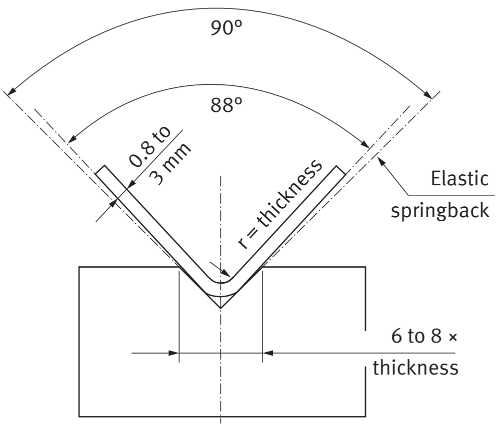


Fig. 2.3.3 - Closed die bending

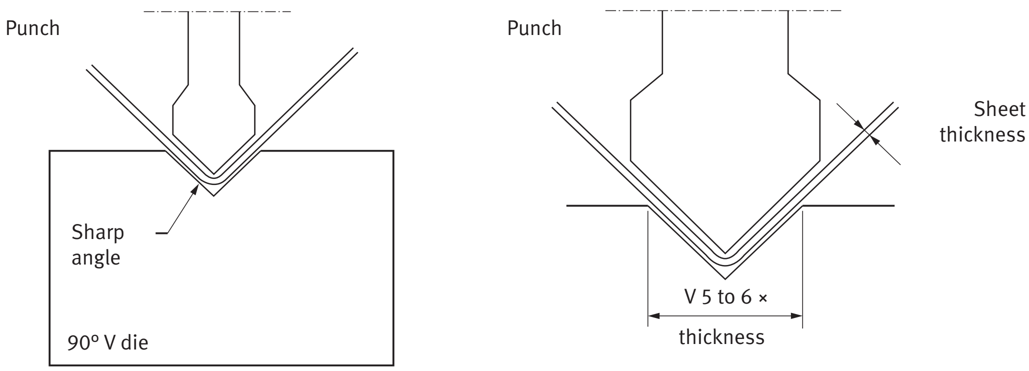


Fig. 2.3.4 - Closed die bending with angle forging

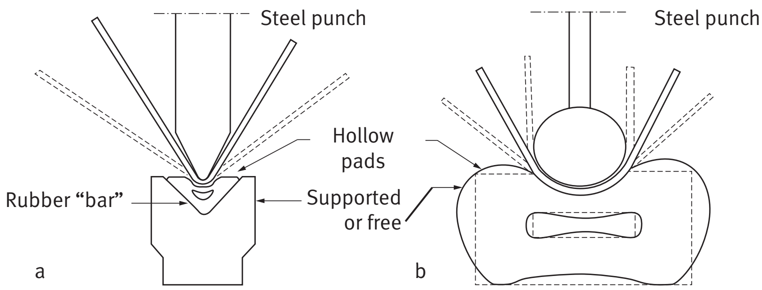
Rubber pad bending

For fine work, where the sheet surfaces must not be damaged, it is recommended to perform the bending operation in a die composed of a rubber pad of appropriate hardness (Shore). In fact, the rubber pad replaces the conventional hardened steel die and enables the bending of complex parts and sections such as those used in decorative applications. This method can be employed for stainless steel sheet thicknesses generally between 0.4 and 1.5 mm and has two major advantages:

a) it is possible to replace a large number of costly steel dies by a single rubber pad;
b) the sheet surface in contact with the pad remains in perfect condition, avoiding the need for expensive subsequent polishing operations.

The possibilities offered by this method are illustrated in figure 2.3.5a for a V bend and in figure 2.3.5b for a circular section bend.

Fig. 2.3.5
a - V-bending on a rubber pad
b - Circular bending on a rubber pad



Calculation of the developed length of a profiled sheet

Since the metal flows freely during bending, the inner fibers are in compression and become shorter, while the outer fibers are in tension and are elongated. Only the neutral fiber does not change length and is therefore used to calculate the developed area for medium and thick gage sheet. For thin sheets, less than 1 mm thick, the calculation is based on the innermost fiber.

Elastic springback

The degree of elastic springback depends on the grade of stainless steel concerned, its mechanical properties, particularly the amount of cold work, and on the geometry of bending, including the bend radius and angle and the thickness of the sheet. Based on these parameters, relations are available for determining the punch and die angles necessary to produce a desired permanent bend angle after removal of the loads. For example, when the radius of curvature is equal to the sheet thickness, the tool angle must be 0.97 times the desired bending angle for the X5CrNi18-10 / 1.4301 grade in the annealed condition, the ratio being only 0.90 for the same material in the half hard condition.

Three-roll forming

General features

Three-roll forming machines are used to produce components such as cylinders from sheet. Machines designed for mild steels can usually be employed for stainless grades, but their capacity will be reduced by about 30%.

The three-roll forming operation

Before rolling, the end of the sheet to be inserted in the machine is generally prepared by bending in a press using a cylindrical punch. In the pyramid type machines usually employed, the cylinder radius is adjusted by an inner bending roll covering between 1/8 and 1/6 of the section. The developed area is calculated in the same way as for bending.

Drawing

Principle and theoretical basis

Drawing is a forming operation used to produce hollow objects from a flat sheet or blank. It is a complex process in which the metal goes through a number of states involving different combinations of tensile and compressive loading. The overall state of strain in a sheet element can be correctly described in terms of the strains in the three principal directions:

- in the "longitudinal" direction (parallel to the principal metal flow):
  $\varepsilon_1 = ln(l/l_o)$, where l_o is the initial length of the element and l the final length;
- in the "transverse" direction, (in the plane of the sheet, perpendicular to the principal metal flow):
  $\varepsilon_2 = ln(w/w_o)$, where w_o is the initial width of the element and w the final width;
- in the thickness direction:
  $\varepsilon_3 = ln(t/t_o)$, where t_o is the initial thickness of the element and t the final thickness.

Since the volume is conserved during deformation, $\varepsilon_1 + \varepsilon_2 + \varepsilon_3 = 0$.

Two principal modes of deformation are distinguished in drawing, namely biaxial expansion or stretching (fig. 2.3.6), which

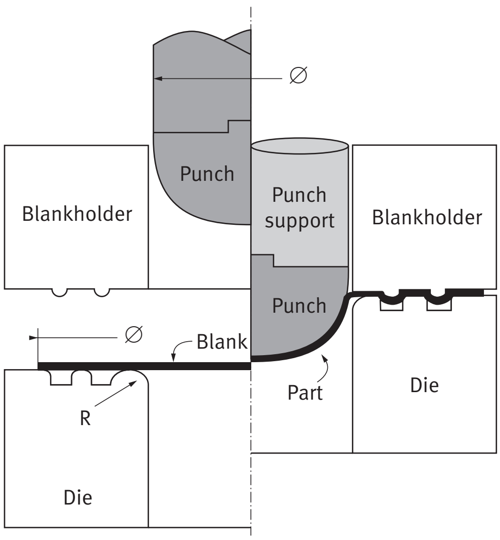


Fig. 2.3.6 - Stretching (biaxial expansion) forming mode: the blank is constrained between the die and the blankholder

occurs when the blank is constrained between the blankholder and the die, and drawing or plane strain compression (fig. 2.3.7), in which the metal is drawn inwards, slipping between the die and the blankholder to form the walls or skirt of the part. In the stretching mode, the cylindrical punch has a hemispherical nose, while in the drawing mode, the punch nose is flat. Figure 2.3.8 shows the principal deformation modes as they appear in the cups produced in various drawability tests (Swift, Erichsen, etc.).

The most faithful representation of the deformations in a part during and after forming is given by the corresponding true strains, which can be represented in a two-dimensional diagram whose orthogonal axes are the principal strains ε_1 and ε_2. The region of stretching is defined roughly by the area between the lines $\varepsilon_1 = \varepsilon_2$ and $\varepsilon_1 = -2\varepsilon_2$. The region of drawing is defined approximately by the area between the lines $\varepsilon_1 = -2\varepsilon_2$ and $\varepsilon_1 = -\varepsilon_2/2$. In the drawing mode, the most significant feature is the increase in thickness ($\varepsilon_3 > 0$) at the top of the skirt, whereas in the stretching mode, the metal tends to be thinned ($\varepsilon_3 < 0$) beneath the punch nose.

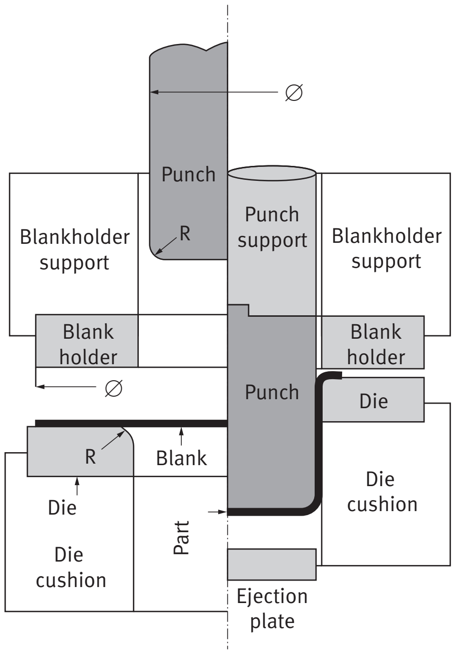


Fig. 2.3.7 - Deep drawing forming mode: the blank slips between the die and the blank-holder

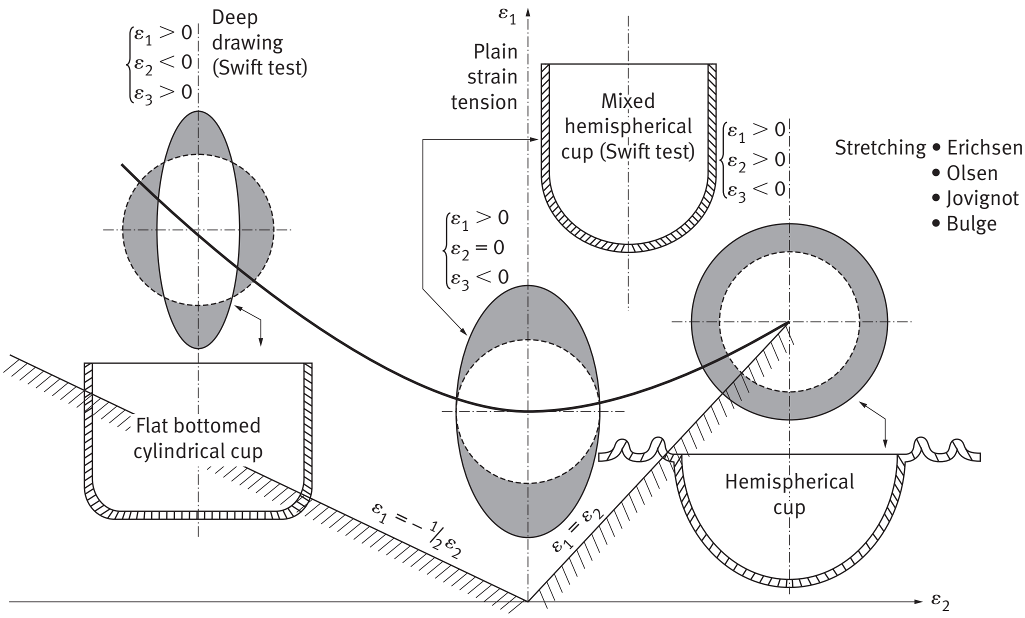


Fig. 2.3.8 - Principal deformation modes in drawing, illustrated by the different types of cupping test

In the Swift test, a circular blank is allowed to slip between the blankholder and the die due to the action of a 33 mm diameter flat nosed punch. This method is used to determine the limiting drawing ratio (LDR), which is defined as the maximum ratio between the blank diameter and the fixed punch diameter for which drawing can be completed without failure (LDR = maximum blank diameter/punch diameter). The results given in Table 2.3.1 were obtained for the grades considered previously.

Even though the overall drawing capacity of austenitic stainless steels (Fe-Cr-Ni alloys) is better than for ferritic grades (Fe-Cr alloys), the table shows the excellent performance of the titanium-stabilized 17% Cr alloy. For drawn parts of this type, this ferritic material can often be a useful substitute for more expensive austenitic grades.

The most widely used drawability techniques are the Erichsen test for the stretching mode and the Swift test for the drawing mode. In the Erichsen test, the blank is tightly clamped between the die and the blankholder and the metal is deformed until the onset of necking, which immediately precedes failure, at which point the drawing depth or "Erichsen deflection" is measured.

Table 2.3.2 gives the Erichsen deflections for the same grades, for an initial blank thickness of 0.8 mm. The superior performance of the austenitic grade X5CrNi18-10 in this deformation mode is clearly apparent.

From a more fundamental viewpoint, the aptitude of a stainless steel for forming can be deduced from its true stress-true strain curve $\sigma = f(\varepsilon)$ determined by tensile testing. In particular, this curve reveals the strain hardening behaviour, while the area beneath the curve represents the work expended to produce a given amount of deformation. The slope of the curve at any point corresponds to the strain hardening rate. The true stress-true strain curve is generally described by the relation $\sigma = f(\varepsilon) = k\varepsilon^n$. The exponent n is called the *strain hardening coefficient*, and is a convenient measure of the work hardening behaviour, since it is constant over a range of strain and can be determined from the slope of the $\ln \sigma = f(\ln \varepsilon)$ curve. Furthermore, for tensile tests on flat specimens, in addition to the longitudinal deformation (ε_1), the true strain can be measured in the width (ε_2) and thickness (ε_3) directions, the latter two values showing a proportional relationship given by $r = \varepsilon_2/\varepsilon_3$, the parameter r being known as the strain ratio. It provides a good indication of the tendency of a sheet metal to thicken or thin during a forming operation. Thus, if $r < 1$, the metal will tend to thin rather than thicken, whereas the opposite will be true if $r > 1$.

The plastic strain ratio usually depends on the direction of the deformation with respect to the sheet rolling direction. In order to characterize the anisotropy of a sheet

European designation: EN 10088-2		LDR
Name	Number	(limiting drawing ratio)
X6Cr17	1.4016	2.05–2.10
X3CrTi17	1.4510	2.15–2.25
X5CrNi18-10	1.4301	2.00–2.05

Table 2.3.1 - Limiting drawing ration (LDR) determined by the Swift test on 0.8 mm thick circular blanks

European designation: EN 10088-2		Erichsen deflection
Name	Number	(mm)
X6Cr17	1.4016	8.7
X3CrTi17	1.4510	9.6
X5CrNi18-10	1.4301	11.5

Table 2.3.2 - Erichsen deflections for 0.8 mm thick ferritic and austenitic stainless steel blanks

material, r is measured at angles of 90°, 45° and 0° to the rolling direction, and anisotropy coefficients are defined as follows:

- the normal strain ratio:
  $r_n = (r_o + r_{90} + 2\, r_{45})/4$
- the planar strain ratio:
  $\Delta r = (r_o + r_{90} - 2\, r_{45})/2$

The latter relation does not always correctly describe the behaviour of stainless steels, for which the following formula is often preferred

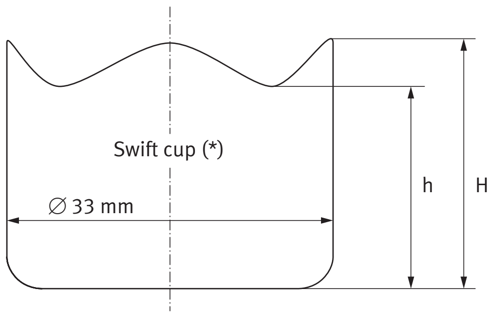
$$\Delta r = [(r_o - r_n)^2 + (r_{90} - r_n)^2 + (r_{45} - r_n)^2]^{1/2}$$

The normal strain ratio r_n gives a good indication of the aptitude for deformation in the drawing mode, while the planar strain ratio Δr can be correlated with the height of the "ears" formed during drawing (fig. 2.3.9). In general, there is a quite good correlation between the strain hardening coefficient n, the normal strain ratio r_n and the results of Erichsen (stretching) and Swift (drawing) tests.

For forming operations where the major deformation mode is stretching, it is preferable to choose a material with a high n value. Conversely, when the drawing mode is predominant, the material should have a high normal strain ratio r_n. In fact, the parameters n and r_n are intrinsic overall characteristics of the material, whereas the critical phenomena during drawing occur locally (necking and fracture). The significance and usefulness of n and r_n are therefore only relative. They give a general indication of the deformation behaviour of different materials, and therefore of their drawability, but remain insufficient for analyzing a specific problem. Table 2.3.3 gives characteristic values of n, r_n and Δr for the major ferritic and austenitic stainless steel grades used for drawing.

The local phenomena mentioned above (necking, fracture) can have several causes. Some of them are related to microstructural parameters, such as the grain size, the dimensions and distribution of inclusions and/or precipitates, and the surface roughness which influences lubricant retention, etc. Other more technological factors often play a decisive role, the most important ones being the clearance between the punch and the die, the blankholder pressure, the punch and die radii, the nature of the tools and their surface quality, and finally, the type of lubricant.

Fig. 2.3.9 - Earing tendencies for different stainless steel grades



(*) – Initial blank diameter: 62.5 mm

$$\text{Earing index}(\%) = \frac{H - h}{H + h} \times 200$$

European designation Name	Number	Δr	Earing index (%)
X6Cr17	1.4016	0.50	8 to 12
X3CrTi17	1.4510	0.35	4 to 6
X5CrNi18-10	1.4301	0.45	5 to 7

Table 2.3.3 - Normal and planar strain ratios and strain hardening coefficients for different grades

European designation: EN 10088-2 Name	Number	r_n	Δr	*n*
X6Cr17	1.4016	1.1/1.6	0.50	0.20/0.25
X3CrTi17	1.4510	1.6/2.0	0.35	0.22/0.28
X5CrNi18-10	1.4301	1.0/1.3	0.45	0.50/0.70

Forming limit curves

The local deformations during and after forming are described in terms of the principal true strains, ε_1 in the longitudinal direction (sometimes denoted ε_r for radial strain in the case of circular parts), and ε_2 in the transverse direction (or ε_c for circumferential strain in circular parts). The various combinations of these two principal strains that lead to the onset of either necking or fracture can be plotted on a diagram, to give so-called forming limit curves. Figures 2.3.10 and 2.3.11 show such curves respectively for the 17% Cr ferritic grade X6Cr17/1.4016 and the 18% Cr-9% Ni austenitic alloy X5CrNi18-10/1.4301. Since only positive elongations are possible in drawing, only this part of the ordinate (ε_1) scale is shown. The ordinate axis separates regions of lateral expansion ($\varepsilon_2 > 0$) and shrinkage ($\varepsilon_2 < 0$). The principal strains ε_1 and ε_2 can be measured either from the overall dimensional changes of simple test specimens or, more generally, from the local deformation of grids printed on the surface of blanks prior to drawability tests. The grids used for measuring the principal strains are generally composed of overlapping 2 mm diameter circles, produced by electrochemical etching. Their dimensions are measured using an optical system of the profile projector type, at a ten times magnification. The forming limit curves shown in figures 2.3.10 and 2.3.11 are based on six types of tests, namely smooth and notched specimen tensile tests, and Erichsen, Olsen, Bulge and Swift cupping tests, using different lubricants.

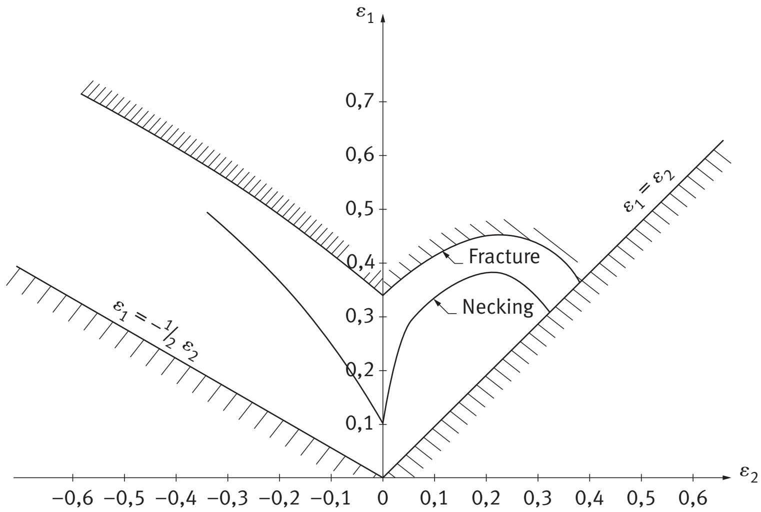


Fig. 2.3.10 - Forming limit curves for X6Cr17 /1.4016

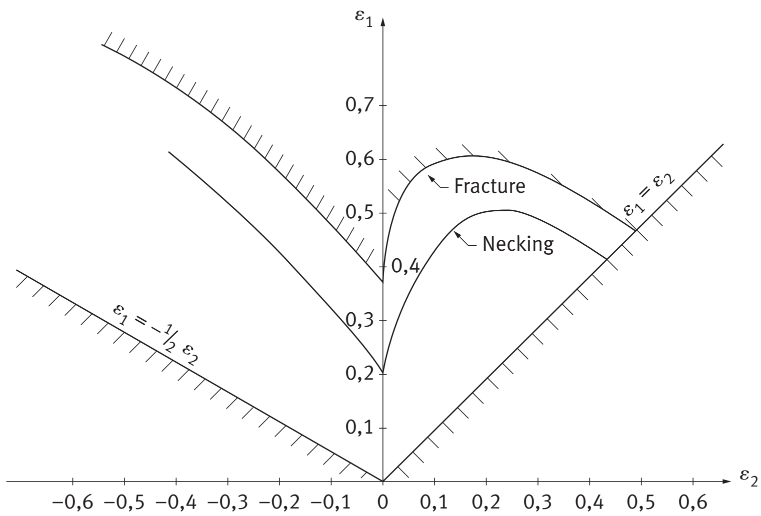


Fig. 2.3.11 - Forming limit curves for X5CrNi18-10 /1.4301

When plotting forming limit curves, it is assumed that the strain paths are linear, i.e. that the ratio $\varepsilon_2/\varepsilon_1$ remains constant. However, this is not true in practice and recent studies have shown that the actual strain path affects the position of the forming limit curve. Thus, if the initial deformation is in the drawing mode and the final deformation is in biaxial stretching or expansion, necking or fracture will occur at a point well above the forming limit curves determined in the above manner. If deformation begins in the stretching mode and finishes in the area of drawing, necking and fracture will occur slightly below the conventionally established forming limit curves.

Nevertheless, in practice, the determination of strain contours on real drawn parts, together with a knowledge of the forming limit curves, provides a useful means of analyzing a forming operation. If the measured limiting strain contour is close to the forming limit curve, the risk of failure for a series of parts will be high. If, on the contrary, it is well below the forming limit curve, then the risk will be small.

Modeling

Modeling is the mathematical simulation of a drawing operation by the so-called finite elements technique, in which the blank is divided into a large number of small volume elements represented by a mesh. In modern simulation softwares, the behaviour of each element is determined from the constitutive equations (flow laws) for the material concerned, taking into account the friction conditions encountered by the blank between the die and the blankholder and beneath the punch. It is also possible to use such models “in reverse”, in order to calculate the optimum blank geometry for a given final part shape.

Tooling

The nature of the tooling is of great importance, since it has a decisive influence on the friction conditions and therefore on metal flow during the forming operation. For deep drawing, aluminum bronzes give the best performance. For very high pressures, it is possible to use either a 13% chromium martensitic stainless steel treated to 60 HRC, or an alloy cast iron, whose friction coefficient is intermediate between those of aluminum bronze and steel.

The punch radius should be such as to allow the metal to flow over it without risk of tearing. For ferritic stainless steels, the minimum punch radius is of the order of six times the sheet thickness, whereas for austenitic grades, it is possible to go down to four times the blank thickness. The die radius *R* is essentially determined by the blank diameter *D*, the punch diameter *d* and the sheet thickness *t*. For the first pass, the relation used is:

$$R = 0.8\,[t \times (D - d)]^{1/2}$$

For subsequent passes, the die radius for the pass *n* is taken as $R_n = (d_{n-1} - d_n)/2$, where d_{n-1}, and d_n are the punch diameters for the passes *n*-1 and *n*. The clearance between the punch and die must be sufficient to allow the metal to flow freely. In practice, it is taken equal to twice the blank thickness plus twice its thickness tolerance plus twice the increase in thickness due to drawing plus twice the thickness of the lubricant film.

Lubrication

Good lubrication of the blank and the tooling is essential for successful drawing. Since stainless steels are generally smoother than other materials subjected to drawing, particular care is necessary to avoid altering the surface appearance and to prevent sticking phenomena detrimental to tool life. Moreover, for parts where an attractive appearance is important, the lubricant must be easy to remove, particularly if it contains corrosive species.

Among the most commonly used lubricants are soluble mineral oils with an addition of about 20% of water, and the so-called "high pressure" mineral oils, which are well adapted to deep drawing. The latter products may contain chlorinated compounds, and if so, they must imperatively be removed by thorough washing and rinsing in order to avoid corrosion of the drawn parts.

Blanks are often coated with a plastic film between 20 and 100 µm thick before drawing, which both serves as a lubricant and protects the surface. Thick PVC-based coatings enable deep drawing operations in a single pass, while thin polyethylene-based films are used for shallow drawing operations, which are always carried out in a single pass.

Example application

The example described below is only one of many applications involving the drawing of stainless steels, but serves to illustrate the general approach followed. It concerns a flat-bottomed cylindrical part 115 mm in diameter and 260 mm high produced from 1 mm thick X5CrNi18-10 austenitic stainless steel sheet. The transition radius between the bottom and the side wall is 10 mm. It is thus quite clearly a deep drawn component.

The appropriate blank diameter is determined from charts, based on the finished part geometry. In this case the blank diameter is 365 mm. Since the height of the part (260 mm) is more than twice its diameter (2 x 115 = 230 mm), it cannot be produced in a single pass. The reduction ratios, i.e. the permissible ratios between the punch diameter and the initial or intermediate blank diameter, are given in Table 2.3.4.

With a reduction ratio of 0.55 for the first pass, the diameter of the first intermediate blank will be 365 x 0.55 = 200 mm. In order to attain the required final diameter, three more passes will be necessary, with a reduction ratio of the order of 0.8. Thus, in the second pass the diameter can be reduced to

Table 2.3.4 - Reduction ratios between the punch and initial or intermediate blank diameters for different types of stainless steel

European designation according to EN 10088-2		Ratio of punch and blank diameters (first pass)	Ratio of punch and blank diameters (Subsequent passes)
Name	Number		
X6Cr17	1.4016	0.60	0.80
X3CrTi17	1.4510	0.52	0.80
X5CrNi18-10	1.4301	0.55	0.80

200 x 0.8 = 160 mm, while the use of a reduction ratio of 0.85 for the third and fourth passes, gives 160 x 0.85 = 136 mm and 136 x 0.85 = 115 mm. In this example, the cumulative reduction ratios are 0.55 after the first pass, 0.44 after the second pass, 0.37 after the third pass and 0.31 after the fourth pass.

The increasing amount of cold work from one pass to the next makes the metal gradually stronger, and beyond a hardness of about 35–40 HRC it is impossible to draw it further. This value is attained for a cumulative reduction ratio of about 0.40. In order to restore the initial formability, it is necessary to perform an annealing treatment. If the atmosphere employed is oxidizing, subsequent pickling and passivation will be essential. In the example above, a cumulative reduction of 0.40 is almost attained after the second pass, so that it is at this stage that the annealing treatment must be performed.

Particular behaviour of certain grades during drawing

"Roping" and "ridging"

Unstabilized ferritic stainless steels, also called semi-ferritic stainless steels, are prone to the surface phenomena known as "roping" and "ridging" after certain forming operations, such as contour forming followed by bending, or drawing. The most representative grade in this family is X6Cr17/1.4016. "Ridging" describes the overall profile of the deformed surface and includes both the microgeometry and the "roping" undulations caused by the deformation (e.g. about 15% elongation in a tensile test) (fig. 2.3.12).

The addition of a stabilizing element, such as titanium, modifies the crystallographic texture due to rolling and minimizes roping. Since the surface microgeometry depends mainly on grain size, the effect of stabilizing additions is only of second order. The titanium stabilized grade X3CrTi17/1.4510 gives quite remarkable results in this respect, and for this reason, its use has become widespread as a replacement for austenitic grades in applications involving deep drawing.

Although they have excellent surface properties and therefore good polishability, niobium-stabilized grades are more subject to ridging. Stabilization with an appropriate combination of titanium and niobium would therefore appear to offer a promising solution for the future.

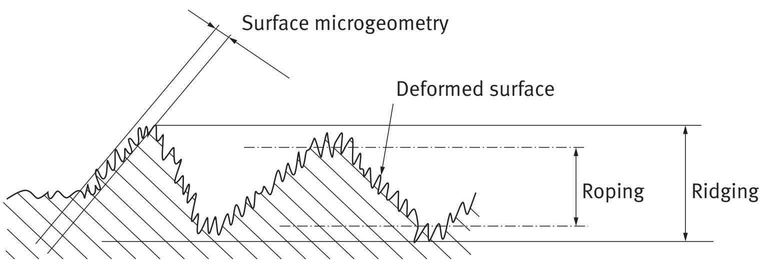


Fig. 2.3.12 - Schematic representation of ridging in a ferritic stainless steel

Delayed cracking

Unstable austenitic stainless steels tend to be subject to the phenomenon of delayed cracking when they are significantly deformed by deep drawing. This is due to the strain-induced transformation of a certain amount of austenite to martensite during the forming operation. Such transformation depends both on the chemical composition of the steel and on the temperature and strain rate during forming. Martensite formation can be beneficial in stretching, since the associated strain hardening limits the tendency for necking. However, in regions of thick components where the deformation mode is of the drawing type, the presence of excessive strain-induced martensite can cause delayed cracking, when the drawing ratio is higher than a critical value for the temperature concerned (fig. 2.3.13). For example, for an unstable 17% Cr–7% Ni austenitic grade deformed at 20 °C, the risk of delayed fracture appears for drawing ratios greater than 1.5.

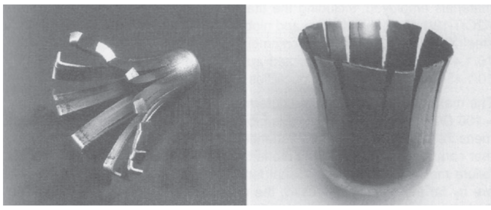


Fig. 2.3.13 - Examples of "delayed cracking" in austenitic stainless steel cups produced in conditions of severe drawing. On the left: flat bottomed cylindrical cup with flange. On the right: flat bottomed cylindrical cup

In order to minimize this risk, the shape of the blank must be carefully optimized with respect to the final part geometry, and the cut-out must be of good quality. Furthermore, the different operations must be performed in close succession, in such a way as to maintain the part at a controlled temperature (warm forming). Finally, the finished part must be trimmed immediately after the final pass. In any doubt, a stress-relieving treatment of at least two hours should be performed at a temperature of about 200 °C.

Tube bending

The bending of stainless steel tubes is an increasingly common operation, particularly due to their extensive use in automobile exhaust systems. All the materials employed, including the titanium stabilized 11% Cr ferritic grade X2CrTi12/1.4512, the titanium and niobium stabilized 17% Cr ferritic stainless steel X2CrTiNb18/1.4509, the common austenitic grades such as X5CrNi18-10/1.4301 and titanium stabilized austenitic grades such as X6CrNiTi18-10/1.4541, possess excellent ductilities particularly favorable for bending.

The maximum elongation in the outermost fiber is given by the formula e (%) $= 100\, D/2R$, where D is the outside tube diameter and R is the bending radius measured at the tube axis. Experience shows that the maximum elongation that can be supported by the tube is 5 to 30% higher that the elongation to failure measured in a conventional tensile test. For thin walled tubes, which are by far the most widely used, the ratio between the diameter D and the thickness t is defined by the inequality $15 < D/t < 40$. In this

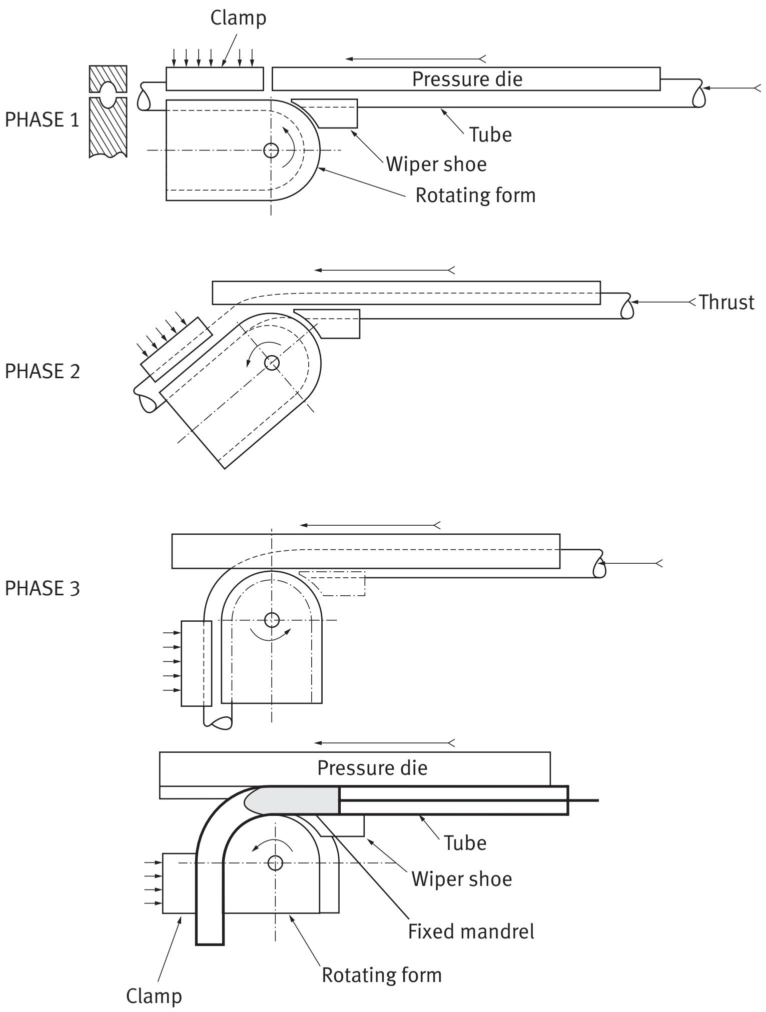
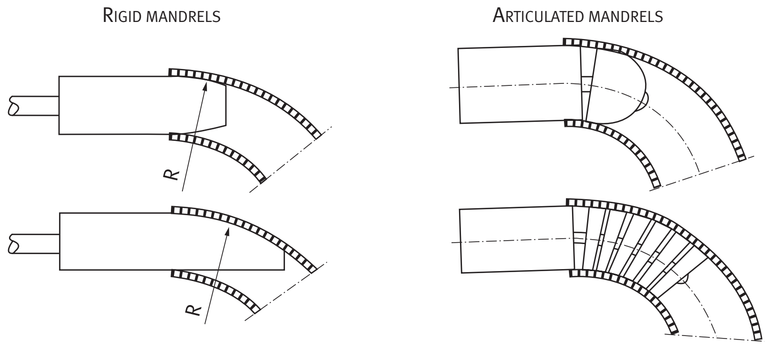


Fig. 2.3.14 - Tube bending machine

geometry range, bending ratios *R/D* close to 1 can be obtained with modern machines, for both ferritic and austenitic grades. In order to attain this level of performance, it is necessary to use draw bending machines equipped with a mobile pressure die and a wiper shoe, together with a system for exerting a thrust on the tube during bending (fig. 2.3.14).

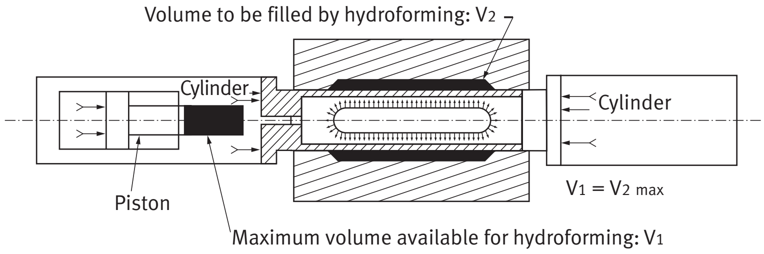
The fixed internal mandrel (fig. 2.3.15) also plays a vital role. Rigid mandrels are suitable for large bending radii, while articulated mandrels are better adapted for smaller radii. However, in order to use articulated mandrels correctly, the machine must have a powerful mandrel extraction system with a large travel. Finally, lubrication is an important process parameter, and must be sufficient to facilitate sliding of the tube over the mandrel. Because of the high pressure exerted by the tube wall on the mandrel, it is necessary to use "extreme pressure" oils. The oil must be introduced automatically from the mandrel in order to ensure reproducible lubrication.

Fig. 2.3.15 - Tube bending mandrels



Tube hydroforming

Fig. 2.3.16 - Principle of the hydroforming of tubes



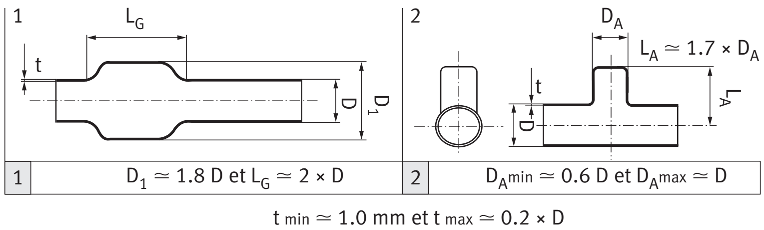


Fig. 2.3.17 - Characteristic geometries of hydroformed X15CrNiSi20-12/1.4828 austenitic stainless steel tubes

Although this technique has been used for more than 30 years for the manufacture of austenitic stainless steel expansion bellows, it has recently gained popularity due to technological improvements in hydroforming machines for tubes. A fluid under a pressure of about 3000 bars can now be injected inside the tube to be formed, a major advantage being that the operation lasts only a few seconds. In this process, the stainless steel is loaded only in the stretching mode, enabling maximum benefit to be drawn from its excellent ductility (fig. 2.3.16). Furthermore, local strain differences are avoided, making it easier to predict the behaviour from forming limit curves. Finally, since the punch used in conventional forming is replaced by a hydraulic fluid, lubrication problems are eliminated.

The first parts produced using the tube hydroforming process were automobile exhaust system components, particularly manifolds, in X15CrNiSi20-12/1.4828 (fig. 2.3.17) and X6CrNiTi18-10/1.4541 grades. Complex geometry parts in X5CrNi18-10/1.4301 have also been produced from predrawn cylindrical blanks.

Lathe spinning

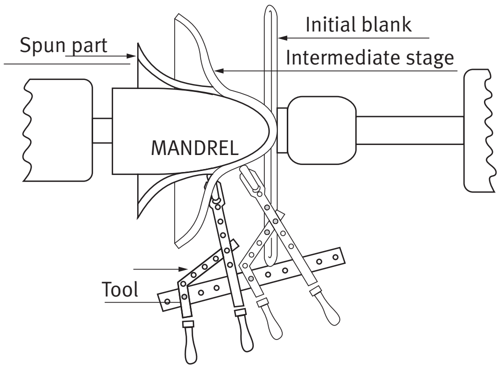


Fig. 2.3.18 - Principle of lathe spinning

In this process, a tool presses a rotating circular blank over a mandrel of circular symmetry (the mandrel is driven by the lathe and rotates the blank). The tool is supported on a rest and is oriented manually. Forming is performed gradually, in several passes, until the blank is in contact with the mandrel over the whole of its useful area. There is virtually no thinning of the sheet, and spinning can be considered to be essentially a constant thickness forming process (fig. 2.3.18). The force exerted on the tool produces mainly compressive stresses, leading to rapid work hardening. For this reason, lathe spinning is limited to thin gage sheet, generally between 0.3 and 2.0 mm.

The stainless steels best adapted to this process are those with low yield strengths and which work harden only slowly under the prevailing compressive stresses. In this respect, the standard ferritic alloy X6Cr17/1.4016, and especially the titanium and/or niobium stabilized grades (e.g. X3CrTi17/1.4510, X2CrTiNb18/1.4509), are particularly appropriate, due to their low strain hardening rates. For stable austenitic stainless steels little prone to the formation of strain-induced martensite, the peripheral forming speeds depend on the blank diameter. For small blanks, with diameters of the order of 200 mm, they are about 600 m/min, but must be reduced to around 300 m/min for larger sizes, of the order of 800 mm.

Lubrication is important in this process, in order to prevent the tool from sticking to the workpiece, which can cause surface defects. Because of the pressures involved, "high pressure" mineral oils must be used.

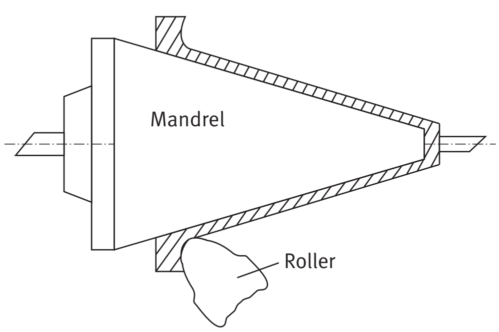
While lathe spinning requires a relatively small capital investment compared to drawing, the productivity is fairly low. The process is therefore used essentially for prototyping and small series manufacture. However, the deformation mechanisms involved in spinning are different from those in drawing, so that if the technique is used to make prototypes, a completely new study must be made before series manufacture by deep drawing.

Flowturning

Flowturning is basically quite similar to spinning, and indeed, is often referred to as "power spinning" or "shear spinning" or "compression spinning". However, a major difference is that the sheet thickness is deliberately reduced, so that it is in fact a stretching operation. The tool is a rotating roller which is displaced perpendicular to the mandrel surface, against which it squeezes the blank. The tool rest is hydraulically or mechanically powered. The inside shape of the finished part corresponds rigorously to the geometry of the mandrel (fig. 2.3.19). The shapes most commonly produced using this technique are cones, with apex angles between 10° and about 60°. Compared to lathe spinning, the wall thickness is better controlled. Depending on the component geometry and the type of stainless steel (ferritic or austenitic), reductions in thickness of up to 60% are commonly attained.

A variant of this process, which can be called cylindrical flowturning, is used to produce hollow components with very large height/diameter ratios, starting from a drawn flat-bottomed cylindrical blank. Depending on the type of stainless steel and the nature of the forming roller, the tool translation speed in this case varies between 200 and 800 mm/min.

Fig. 2.3.19 - Principle of flowturning



2.4 Hot forming

Whenever possible, it is preferable to use cold forming processes, since hot forming inevitably causes surface oxidation of the stainless steel, decreasing its wet corrosion resistance. When hot forming cannot be avoided, it is necessary to reform the passive layer by a subsequent pickling and repassivation treatment.

Photo 7: The glass-steel structure "La lentille de la cour de Rome" (The lens of the Rome yard) – Paris (F)

Hot forming of austenitic stainless steels

Hot forming is essentially used for heavy gage sheet. It must be carried out in the temperature range between 950 and 1300 °C, and it is essential to avoid prolonged residence between 500 and 900 °C during either heating or cooling. If the cooling is sufficiently rapid, additional annealing is not necessary. If this is not the case, annealing must be performed at 1100 °C, followed by rapid cooling to ambient temperature.

Hot forming of ferritic stainless steels

In this case, hot forming is carried out between 850 and 1100 °C. In non-stabilized grades, there is a high risk of sensitization due to the precipitation of chromium carbides at grain boundaries during subsequent cooling, leading to a marked loss in corrosion resistance. In order to prevent this risk, it is essential to perform a post-forming annealing treatment between 750 and 850 °C, followed by rapid water or air cooling.

Hot forming of austenitic-ferritic duplex stainless steels

Hot forming must imperatively be performed above 950 °C. If the temperature is maintained above this value throughout the forming operation and if the subsequent cooling is rapid, further annealing is not necessary. If this is not the case, treatment at 1100-1150 °C followed by rapid cooling is essential.

Photo 8: Hot extruded sections, used for the glass-steel structure "La lentille de la cour de Rome" (The lens of the Rome yard) – Paris (F)

Hot tube bending

The vast majority of tube bending operations are carried out at ambient temperature. However, in certain rare cases, it may be necessary to bend tubes in situations where a bending machine is not available. Bending can then be satisfactorily performed at high temperature by the following procedure. First of all, one of the tube ends is hermetically closed by welding on a full flange. The tube is then placed in the vertical position and filled with perfectly dry sand, with a grain size of about 100 µm (or 150 mesh) to ensure good flowability and complete filling, carefully compacting it as filling proceeds. When the tube is full, the top end is sealed by welding on another full flange. When prepared in this way, the tube can be heated and bent to the required radius on a suitable form.

Austenitic stainless steel tubes

As indicated in the section "hot forming of austenitic stainless steels", bending must be performed between 950 and 1300 °C. If the heating and cooling are sufficiently rapid, the risk of chromium carbide precipitation between 500 and 900 °C is practically negligible. In these conditions, subsequent annealing and quenching are not necessary. Since heating is generally performed with a torch, care must be taken that the flame is neither reducing nor carburizing, but slightly oxidizing.

Ferritic stainless steel tubes

Bending should be performed between 850 and 1100 °C, according to the recommendations given in the section "Hot forming of ferritic stainless steels". As for austenitic grades, the torch used for heating should be slightly oxidizing.

Finishing operations

Once the tube has been bent and cooled down to ambient temperature, the two ends are cut and the sand is removed. It is then necessary to pickle and passivate both the inside and outside. If the tube is intended to transport a fluid, chemical treatment of the inside is absolutely essential. If it is to serve a decorative purpose, the external surface should be polished with an abrasive of appropriate grain size after chemical pickling.

Appendices

Physical and chemical properties of stainless steels

Why five families?

Stainless steels are iron alloys containing a minimum of approximately 11% chromium which is the key alloying element. Chromium in excess of 11% forms a tenacious protective film on any exposed surface; i.e. a corrosion barrier. To effectively prevent corrosion chromium must be in solid solution form and not combined as chromium carbides.

Martensitic stainless steels

Martensitic stainless steels have the highest carbon content (up to 1.2%). Their mechanical strength can be increased by quenching. The martensitic structure obtained is magnetic.

Ferritic stainless steels

Ferritic stainless steels have a low carbon content ($\leqslant$ 0.08%). For this reason, they do not display significant hardening after quenching. The ferritic structure is magnetic.

In the ferritic grades the toughness of the HAZ may be poor, due to grain growth during welding.

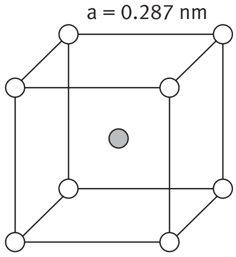
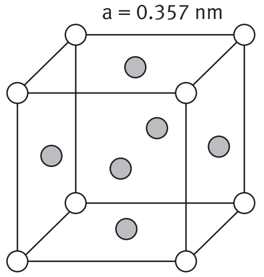


Photo 15: Professional kitchen knive. The blade is made of martensitic stainless steel.



Austenitic stainless steels

These alloys are the most popular grades of stainless steels because of their excellent formability and corrosion resistance. Due to the presence of austenite – stabilizing alloying additions, particularly nickel, these stainless steels have the face-centered cubic austenitic structure. They are not hardenable by heat treatment, but can be strain-hardened by cold-work.

Heat-resisting stainless steels

These iron – chromium – nickel grades have high strength at elevated temperatures and resistance to carburizing atmospheres. The basic chromium content is increased to 20-25% Cr and the nickel varies from 10-35%. All grades optimized for high temperature applications have high carbon contents.

Photo 16: Pump casing: the high ductility of austenitic stainless steels makes them suitable for one-piece designs combining deepdrawing and hydroforming techniques.

Photo 17: Duplex stainless steel bulkhead panels for chemical tankers

Duplex austenitic-ferritic stainless steels

The microstructures of duplex stainless steels consist of a mixture of austenite and ferrite. They exhibit characteristics of both phases with higher strength and ductility. Compared with austenite grades, duplex stainless steels show higher strength and markedly better corrosion resistance in chloride solutions.

Oxidation and oxides

Stainless steels exhibit excellent resistance to oxidizing environments. The one element essential in forming a high-temperature corrosion-resistant layer is chromium (so-called passive layer). The resulting compound is a crystalline oxide or hydroxide.

Oxidation is a process in which the proportion of the electronegative constituent in a compound is increased. In oxidation electrons are removed from the oxidized species.

An oxide is a compound of oxygen with another element. Oxides are divided into *acidic oxides* which react with bases to form salts; *basic oxides* which react with acids to form salts; *amphoteric oxides* which exhibit both basic and acidic properties.

In aqueous systems, an acid is defined as a substance which is capable of forming hydrogen ions when dissolved in water. Most inorganic acids may be regarded as a compound of an *acidic oxide* and water. When the oxide concerned is that of a metal, it may exhibit *amphoteric properties*, sometimes acting as an *acid* and sometimes as a *base*.

Photo 18: Burner part made of heat-resisting ferritic stainless steel

Typical physical properties (according to EN 10088-1)

Physical Properties	Families of Stainless Steel	Martensitic Grades	Ferritic Grades	Austenitic Grades	Austenitic-ferritic Grades
(kg/dm^3)	Density	7.7	7.7	7.9	7.8
(GPa)	Modulus of Elasticity at 20 °C:	215 000	220 000	200 000	200 000
(10^{-6} x K^{-1})	Coefficient of Thermal Expansion between 20 °C and 200 °C:	10.5	10	16	13.0
(W/(m x K))	Thermal conductivity at 20 °C:	30	25	15	15
(J/(kg x K))	Specific Heat Capacity at 20 °C:	460	460	500	500
(v x mm^2/m)	Electrical Resistivity at 20 °C:	0.55	0.60	0.73	0.80

Identification and Designation of Stainless Steels

European Designations

European Specifications which are used throughout the European Union

The European Standards were given the status of a national standard, either by publication of an identical text, or by endorsement, in October 1995, and conflicting national standards were withdrawn in October 1995.

According to the CEN/CENELEC Internal Regulations, the following countries are bound to implement this European Standard: Austria, Belgium, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, Switzerland and United Kingdom.

Principal standards concerning stainless steels

Designation standards

EN 10027-1 Designation for steels – Part 1: Steel names, principal symbols

EN 10027-2 Designation for steels – Part 2: Numerical system

General purposes product standards

EN 10088-1 Stainless Steels – Part 1: List of stainless steels

EN 10088-2 Stainless Steels – Part 2: Technical delivery conditions for sheet/plate and strip for general purposes

EN 10088-3 Stainless Steels – Part 3: Technical delivery conditions for semi-finished products, bars, rods and sections for general purposes

prEN 10088-4 Stainless Steels – Part 4: Technical delivery conditions for sheet/plate and strip of corrosion for construction purposes

prEN 10088-5 Stainless Steels – Part 5: Technical delivery conditions for bars, rods, wire, sections and bright products of corrosion resisting steels for construction puposes

EN 10095- Heat-resisting steels and alloys

Pressure purposes product standards

EN 10028-7 Flat products made of steel for pressure purposes – Part 7: Stainless steels

EN 10272 Rolled bars made of stainless steel for pressure purposes

EN 10216-5 Seamless steel tubes for pressure purposes – Part 5: Technical delivery conditions-Stainless steel tubes

EN 10217-7 Welded steel tubes for pressure purposes – Part 7: Technical delivery conditions-Stainless steel tubes

EN 10222-5 Steel forgings for pressure purposes – Part 5: Martensitic, austenitic and austenitic-ferritic stainless steels

General purposes tube and fittings standards

EN 10296-2 Welded circular steel tubes for mechanical and general engineering purposes – Part 2: Technical delivery conditions-Stainless steel tubes

EN 10297-2 Seamless circular steel tubes for mechanical and general engineering purposes – Part 2: Technical delivery conditions-Stainless steel tubes

EN 10312 Welded stainless steel tubes and fittings for the conveyance of aqueous liquids including water for human consumption: Technical delivery conditions

EN 12502-4 Protection of metallic materials against corrosion – Corrosion likelihood in water conveying systems – Part 4: Review of the influencing factors for stainless steels

Dimensional standards

ISO 9445 Continuously cold-rolled stainless steel narrow strip, wide strip, plate/sheet and cut lengths – Tolerances on dimensions an form (officialy replaced EN 12058 and EN 12059 standards)

Welding consumables standards

EN 439 Welding consumables: Shielding gases for arc welding and cutting – Classification

EN 760 Welding consumables: Fluxes for submerged arc welding – Classification

EN 1600 Welding consumables: Covered electrodes for manual arc welding of stainless and heat-resisting steels-Classification

EN 12072 Welding consumables: Wire electrodes, wires and rods for arc welding of stainless and heat-resisting steels – Classification

ISO 17633 Welding consumables: Tubular cored electrodes and rods for gas shielded and non-gas shielded metal arc welding of stainless and heat-resisting steels – Classification (officialy replaced EN 12073 standard)

Standard Designation of Stainless Steels

The steel names and steel numbers were established in accordance with EN 10027. The European standard for stainless steels is EN 10088 and the designation systems adopted in this standard are the EUROPEAN MATERIAL NUMBER and the MATERIAL NAME.

The material number comprises three parts, for example 1.4301, where: 1 denotes steel 43 denotes one group of stainless steels (austenitic grades without Mo, Nb or Ti) and 01 is the individual grade identification.

The material name system provides some indication of the alloy composition, for example X5CrNi18-10, where: X denotes high alloy steel, 5: 100x % of carbon, Cr Ni: chemical symbols of main alloying elements, 18-10: % of main alloying elements.

Examples

- X20Cr13 / 1.4021
  Steel with a carbon content of 20/100 = 0.2% and a chromium content of 13%.
- X2CrTi12 / 1.4512
  Steel with a carbon content of 2/100 = 0.02% and a chromium content of 12% and with a titanium addition.
- X2CrNiMo17-12-2 / 1.4404
  Steel with a carbon content of 2/100 = 0.02% and a chromium content of 17%, a nickel content of 12%, and a molybdenum content of 2%.
- X2CrNiMoN22-5-3 / 1.4462
  Steel with a carbon content of 2/100 = 0.02% and a chromium content of 22 %, a nickel content of 5%, a molybdenum content of 3%, and a nitrogen addition.

Equivalence between European Number and Name Designations and AISI Designations*

EN Number	European Designation	AISI or commercial designation
1.4000	X6Cr13	410S
1.4002	X6CrAl13	405
1.4003	X2CrNi12	403
1.4016	X6Cr17	430
1.4028	X30Cr13	420
1.4029	X29CrS13	420F
1.4057	X17CrNi16-22	431
1.4105	X6CrMoS17	430F
1.4113	X6CrMo17-1	434
1.4125	X105CrMo17	440C
1.4301	X5CrNi18-10	304
1.4303	X4CrNi18-12	305
1.4305	X8CrNiS18-9	303
1.4306	X2CrNi19-11	304L
1.4307	X2CrNi18-9	304L
1.4310	X9CrNi18-8	301
1.4311	X2CrNiN18-10	304LN
1.4335	X1CrNi25-21	310 S
1.4361	X1CrNiSi18-15-4	18.15
1.4362	X2CrNiN23-4	SAE2304
1.4372	X12CrMnNiN17-7-5	201
1.4373	X12CrMnNiN18-9-5	202
1.4401	X4CrNiMo17-12-2	316
1.4404	X2CrNiMo17-12-2	316L
1.4406	X2CrNiMoN17-11-2	316LN
1.4410	X2CrNiMoN25-7-4	2507
1.4434	X2CrNiMoN17-12-3	317LN
1.4438	X2CrNiMo18-15-4	317L
1.4439	X2CrNiMoN17-13-5	317L4
1.4460	X3CrNiMoN27-5-2	7Mo plus
1.4462	X2CrNiMoN22-5-3	2205
1.4466	X1CrNiMoN25-22-2	310MoLN
1.4501	X2CrNiMoCuWN25-7-4	Zeron 100
1.4507	X2CrNiMoCuN25-6-3	Ferralium 255
1.4509	X2CrTiNb18	441
1.4510	X3CrTi17	430Ti, 439
1.4511	X3CrNb17	430Nb
1.4512	X2CrTi12	409
1.4516	X6CrNiTi12	414
1.4521	X2CrMoTi18-2	444
1.4532	X8CrNiMoAl15-7-2	PH 15.7Mo
1.4537	X1CrNiMoCuN25-25-5	URSB8
1.4539	X1NiCrMoCu25-20-5	904L
1.4541	X6CrNiTi18-10	321
1.4542	X5CrNiCuNb16-4	630 17.4 (PH)
1.4550	X6CrNiNb18-10	347
1.4567	X3CrNiCu18-9-4	XM 7/18.9LW
1.4568	X7CrNiAl17-7	17.7PH
1.4571	X6CrNiMoTi17-12-2	316Ti
1.4580	X6CrNiMoNb17-12-2	316Cb

* Detailed information about the chemical, mechanical and physical properties of stainless steels is available from www.euro-inox.org/technical_tables (an interactive database) or from the printed brochure *Tables of Technical Properties* (Materials and Applications Series, Volume 5), Luxembourg: Euro Inox, 2005

Acronyms and abbreviations

°C : Celsius degree
AISI : American Iron and Steel Institute
AOD : Argon-Oxygen Decarburization (melting process)
ASTM : American Society for Testing and Materials
A-TIG : Activating flux TIG (welding)
AWS : American Welding Society
CERMET : CERamic – METal (machining)
CR : Cold Rolled (rolling)
CVD : Chemical Vapor Deposition (machining)
El. : Elongation (%)
EVA : Ethyl Vinyl Acetate (bonding)
FCAW : Flux Cored Arc Welding (welding)
FW : Flash Welding (welding)
GMAW : Gas Metal Arc Welding (welding)
GTAW : Gas Tungsten Arc Welding (welding)
HAZ : Heat Affected Zone (welding, thermal cutting)
HB : Brinell Hardness number (hardness)
HF : High Frequency (welding, brazing)
HFIW : High Frequency Induction Welding (welding)
HR : Hot Rolled (rolling)
HRB : Rockwell B. Hardness number (hardness)
HRC : Rockwell C. Hardness number (hardness)
HSS : High Speed Steels (machining)
HV : Vickers Hardness number (hardness)
J : Joule (energy) - (metric unit)
K : Crack tip stress field intensity factor (fracture mechanics)
kg : Kilogram
KCV : Charpy impact energy absorption (toughness)
LBW : Laser Beam Welding (welding)
LCC : Life Cycle Costing (global costing)
LDR : Limiting Drawing Ratio (drawing)
MF : Medium Frequency (welding, brazing)
MIG : Metal Inert Gas (welding)
N : Newton (force)
PAW : Plasma Arc Welding (welding)
PVD : Physical Vapor Deposition (machining)
RSW : Resistance Spot Welding (welding)
SAW : Submerged Arc Welding (welding)
SMAW : Shielded Metal Arc Welding (welding)
STT : Surface Tension Transfer (welding)
SW : Seam Welding (welding)
TIG : Tungsten Inert Gas (welding)
UTS : Ultimate Tensile Strength (N/mm^2)
UW : Upset Welding (welding)
WIG : Wolfram Inert Gas (welding)
YAG : Yttrium-Aluminium-Garnet (laser welding, thermal cutting)
YS : Yield Strength (N/mm^2)

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