Duplex Stainless Steel

OUTOKUMPU

Steel grades

Outokumpu	EN	ASTM
LDX 2101®	1.4162	S32101
SAF 2304®	1.4362	S32304
2205	1.4462	S32205
		S31803
SAF 2507®	1.4410	S32750

Characteristic properties

- High strength
- Good to very good resistance to pitting and crevice corrosion
- High resistance to stress corrosion cracking and corrosion fatigue
- Good to very good resistance to uniform corrosion
- Good erosion resistance
- Good fatigue resistance
- High energy absorption
- Low thermal expansion
- Good weldability

Applications

- Heat exchangers
- Water heaters
- Pressure vessels
- Large storage tanks
- Rotors, impellers and shafts
- Components for structural design
- Firewalls and blast walls on offshore platforms
- Digesters and other equipment in the pulp and paper industry
- Cargo tanks and pipe systems in chemical tankers
- Desalination plants
- Flue-gas cleaning
- Seawater systems

General characteristics

Austenitic-ferritic also referred to as duplex stainless steels, combine many of the beneficial properties of ferritic and austenitic steels. Due to their high content of chromium and nitrogen, and often also molybdenum, these steels offer good resistance to local and uniform corrosion. The duplex microstructure contributes to their high strength and high resistance to stress corrosion cracking. Duplex steels also have good weldability.

Outokumpu Stainless produces a whole range of duplex grades from the lean alloyed LDX 2101 up to the super duplex grades SAF 2507 and 1.4501. This publication present the properties of LDX 2101, SAF 2304, 2205 and SAF 2507. The properties of 1.4501 is in general terms very similar to those of SAF 2507.

Chemical composition

The chemical composition of a specific steel grade may vary slightly between different national standards. The required standard will be fully met as specified on the order.

Chemical composition

Table 1

Outokumpu steel name	International steel No		Chemical composition, % Typical values						National steel designations, superseded by EN			
	EN	ASTM	C	N	Cr	Ni	Mo	Others	BS	DIN	NF	SS
4301	1.4301	304	0.04	–	18.1	8.3	–	–	304S31	1.4301	Z7 CN 18-09	2333
4404	1.4404	316L	0.02	–	17.2	10.1	2.1	–	316S11	1.4404	Z3 CND 17-11-02	2348
4436	1.4436	316	0.04	–	16.9	10.7	2.6	–	316S33	1.4436	Z7 CND 18-12-03	2343
904L	1.4539	N08904	0.01	–	20	25	4.3	1.5Cu	904S13	1.4539	Z2 NCDU 25-20	2562
254 SMO®	1.4547	S31254	0.01	0.20	20	18	6.1	Cu	–	–	–	2378
LDX 2101®	1.4162	S32101	0.03	0.22	21.5	1.5	0.3	5Mn	–	–	–	–
SAF 2304®	1.4362	S32304	0.02	0.10	23	4.8	0.3	–	–	1.4362	Z3 CN 23-04 Az	2327
2205	1.4462	S32205*	0.02	0.17	22	5.7	3.1	–	318S13	1.4462	Z3 CND 22-05 Az	2377
4501	1.4501	S32760	0.02	0.27	25	7	3.8	W,Cu	–	–	–	–
SAF 2507®	1.4410	S32750	0.02	0.27	25	7	4	–	–	–	Z3 CND 25-06 Az	2328

* Also available as S31803

Microstructure

The chemical composition of duplex steels is balanced to give approximately equal amounts of ferrite and austenite in solution-annealed condition. The higher the annealing temperature the higher the ferrite content. However, the steel must be heated to a very high temperature to become completely ferritic.

Duplex steels are more prone than austenitic steels to precipitation of phases causing embrittlement and reduced corrosion resistance. The formation of intermetallic phases such as sigma phase occurs in the temperature range 600-950°C and reformation of ferrite occurs in the range 350-525°C (475°C embrittlement).

Exposures at these temperatures should therefore be avoided. In normal welding and heat-treatment operations the risk of embrittlement is low. However, certain risks exist, for example in heat treatment of thick sections, especially if the cooling is slow.

Figure 1 illustrates the relation between time and temperature that leads to embrittlement due to intermetallic phase formation and to 475°C embrittlement.

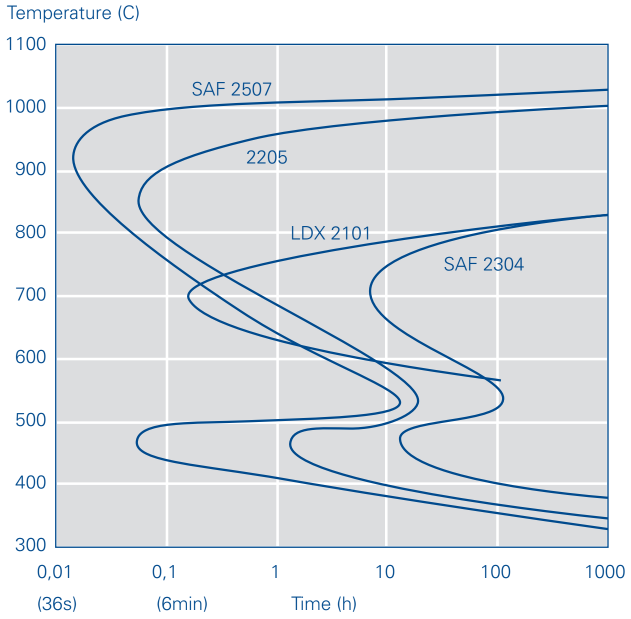

Fig. 1. Curves for reduction of impact strength to 50% compared to solution annealed condition.

Mechanical properties

Tables 2-5 show the mechanical properties of the duplex steels. Data according to EN 10088 when applicable. LDX 2101 is not yet listed in EN 10088, data corresponding to a PMA and to ASTM A240. Permitted design values can vary between different product forms. See the relevant specification for correct values.

Mechanical properties at 20˚C Table 2

			Minimum values			Typical values		
			P	H	C	P (15mm)	H (4mm)	C (1mm)
LDX 2101								
Proof strength	$R_{p0.2}$	MPa	450	480	530	480	570	600
Tensile strength	R_m	MPa	650	680	700	700	770	800
Elongation	A_5	%	30	30	30	38	38	35
Hardness	HB					225	230	230
SAF 2304								
Proof strength	$R_{p0.2}$	MPa	400	400	420	450	520	545
Tensile strength	R_m	MPa	630	600	600	670	685	745
Elongation	A_5	%	25	20	20	40	35	35
Hardness	HB					210	220	225
2205								
Proof strength	$R_{p0.2}$	MPa	460	460	480	510	620	635
Tensile strength	R_m	MPa	640	660	660	750	820	835
Elongation	A_5	%	25	25	20	35	35	35
Hardness	HB					250	250	250
SAF 2507								
Proof strength	$R_{p0.2}$	MPa	530	530	550	550	590	665
Tensile strength	R_m	MPa	730	750	750	820	900	895
Elongation	A_5	%	20	15	15	35	30	33
Hardness	HB					250	265	255

P = hot rolled plate. H = hot rolled coil. C = cold rolled coil and sheet.

Impact toughness. Minimum value[1)] for plate up to 30 mm, Charpy-V, J — Table 3

	LDX 2101	SAF 2304	2205	SAF 2507
20°C	60	60	60	60
-20°C	60	60	60	60
-40°C	40	40	40	40

1) Mean value of 3 full-size test bars

Tensile properties at elevated temperatures. Minimum values, MPa — Table 4

	LDX 2101		SAF 2304		2205		SAF 2507	
	$R_{p0.2}$	R_m	$R_{p0.2}$	R_m	$R_{p0.2}$	R_m	$R_{p0.2}$	R_m
100°C	380	590	330	540	360	590	450	680
150°C	350	560	300	520	335	570	420	660
200°C	330	540	280	500	315	550	400	640
250°C	320	540	265	490	300	540	380	630

Fatigue

The high tensile strength of duplex steels also implies high fatigue strength. Table 5 shows the result of pulsating tensile fatigue tests (R=0.1) in air at room temperature. The fatigue strength has been evaluated at 2 million cycles and probability of rupture 50%. Since the test was made using round polished test bars from hot rolled plate, correction factors for surface roughness, notches, welds etc, are required in accordance with classical theory relating to fatigue failure. As shown by the table the fatigue strength of the duplex steels corresponds approximately to the proof strength of the material.

Fatique, pulsating tensile test, MPa — Table 5

	LDX 2101	SAF 2304	2205	SAF 2507	1.4404
$R_{p0.2}$	478	446	497	565	280
R_m	696	689	767	802	578
Fatigue strength	500	450	510	550	360

Standard deviation of fatigue strength, for the entire population ~ 30 MPa

Physical properties

Physical data according to EN 10088 apply for all our duplex steels.

Typical values

Table 6

		20°C	100°C	200°C	300°C
Density	kg/dm^3	7.8			
Modulus of elasticity	GPa	200	194	186	180
Poissons ratio		0.3			
Linear expansion at (RT → T)°C	X10^{-6}/°C	–	13.0	13.5	14.0
Thermal conductivity	W/m°C	15	16	17	18
Thermal capacity	J/kg°C	500	530	560	590
Electric resistivity	µΩm	0.80	0.85	0.90	1.00

RT = Room temperature

Corrosion resistance

The duplex steels cover a wide range of corrosion performance in various environments. For a more detailed description of their resistance, please refer to our Corrosion Handbook. A brief description follows below regarding their resistance in different types of environment.

Uniform corrosion

Uniform corrosion is characterised by a uniform attack on the steel surface that has come into contact with a corrosive medium. The corrosion resistance is generally considered good if the corrosion rate is less than 0.1 mm/year.

Due to their high chromium content, duplex steels offer excellent corrosion resistance in many media.
LDX 2101 has a better resistance than 1.4301 and in some cases as good as 1.4436. SAF 2304 is in most cases equivalent to 1.4436, and the other more highly-alloyed duplex steels show even better resistance. The isocorrosion diagram in dilute sulphuric acid is shown in Figure 2. In sulphuric acid contaminated by chloride ions, 2205 shows much better resistance than 1.4436 and a similar resistance to that of 904L, Figure 3.

Stainless steel grades such as 1.4301 and 1.4436 have very limited use in hydrochloric acid because of the risk of uniform and local corrosion. High-alloyed steels such as SAF 2507 and to some extent also 2205 can be used in dilute hydrochloric acid, Figure 4. Pitting is normally not a problem in the area below the boundary line but crevices should be avoided.

Phosphoric acid produced according to the wet process always contains corrosive contaminations, e.g. in the form of chlorides and fluorides. 2205 offers very good resistance even in acids that have a fairly high halide content, Figure 5.

In strongly oxidising acids, e.g. nitric acid, non-molybdenum alloyed steels are often more resistant than the molybdenum-alloyed steels. LDX 2101 and SAF 2304 are good alternatives because of their high chromium content in combination with a low molybdenum content.

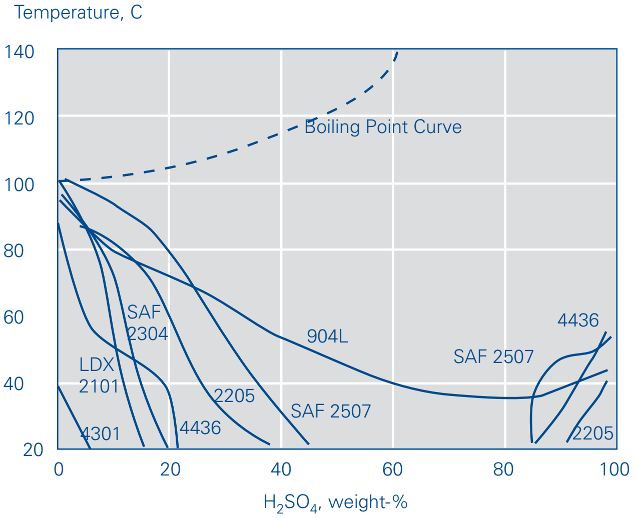

Fig. 2. Isocorrosion curves, 0.1 mm/year, in sulphuric acid.

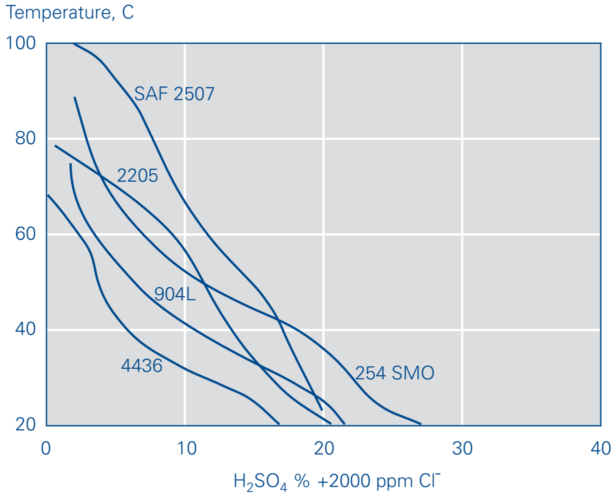

Fig. 3. Isocorrosion curves, 0,1 mm/year, in sulphuric acid containing 2000 ppm chloride ions.

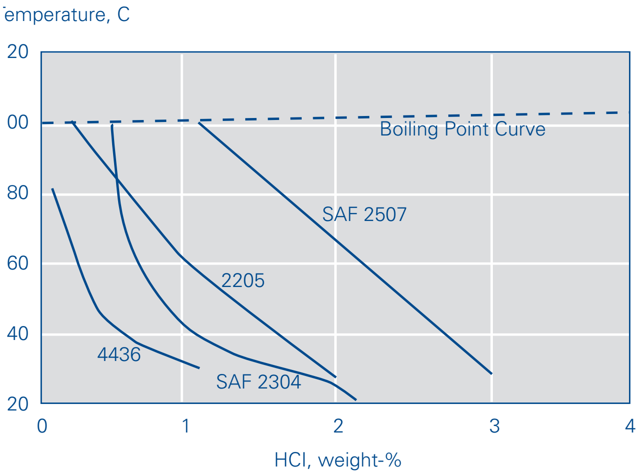

Fig. 4. Isocorrosion curves 0.1mm/year, in hydrochloric acid.

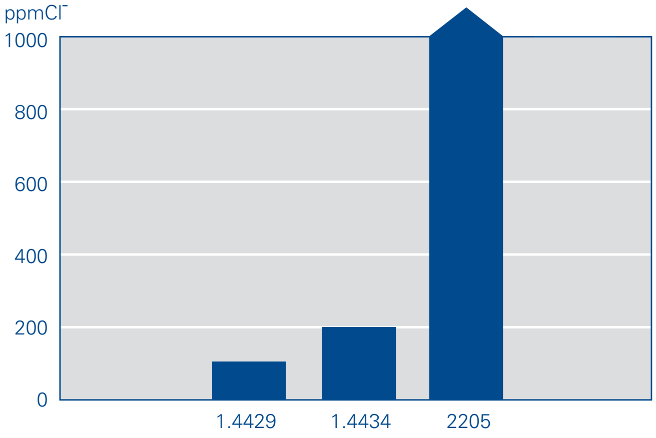

Fig. 5. Maximum acceptable chloride contents in phosphoric acid containing 0.9%Fe_2O_3 and 0.6% Al_2O_3 as inhibitors. The diagram shows limit values for three grades used for chemical tankers.

Pitting and crevice corrosion

The resistance to pitting and crevice corrosion increases with the content of chromium, molybdenum and nitrogen in the steel. Due to their different alloying levels, the four duplex steels show considerable differences in this respect. LDX 2101 has a resistance approaching that of 1.4404. SAF 2304 is on a level with conventional molybdenum-alloyed steels of the 1.4404 type, while 2205 is on a level with 904L and SAF 2507 with 6Mo steels.

There are different methods for comparing the resistance of stainless steels to pitting corrosion in chloride solutions. The electro-chemical method, used by Outokumpu Stainless, makes it possible to measure the resistance to pitting without interference from crevice corrosion (ASTM G 150). The results are given as the critical pitting temperature, CPT, at which pitting is initiated. The pitting corrosion resistance of the steels in a ground (P320 mesh) condition is shown in Figure 6.

The actual value of the as delivered surface may differ between product forms.

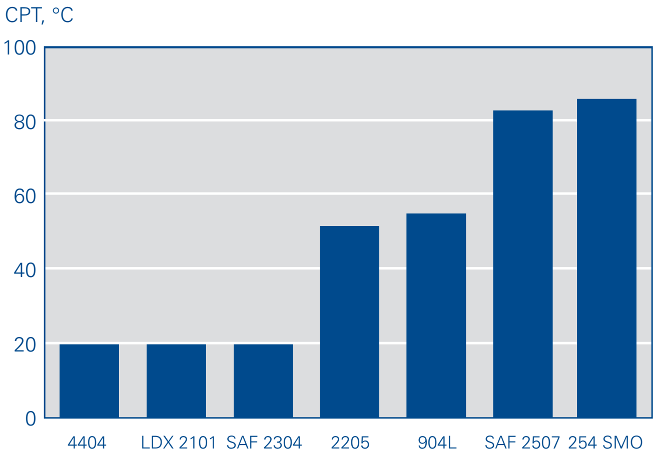

Fig. 6. Typical critical pitting corrosion temperatures (CPT) in 1M NaCl measured according to ASTM G150 using the Avesta Cell. Test Surfaces wet ground to 320 mesh

When ranking the resistance to crevice corrosion, it is common to measure a critical temperature at which corrosion is initiated in a well-defined solution. The typical critical crevice corrosion temperatures (CCT) measured in 6% $FeCl_3$ + 1% HCl according to ASTM G48 Method F, is presented in figure 7. Different products and different surface finishes, e.g. mill finish surfaces, may show CCT values that differ from the values given in the figure.

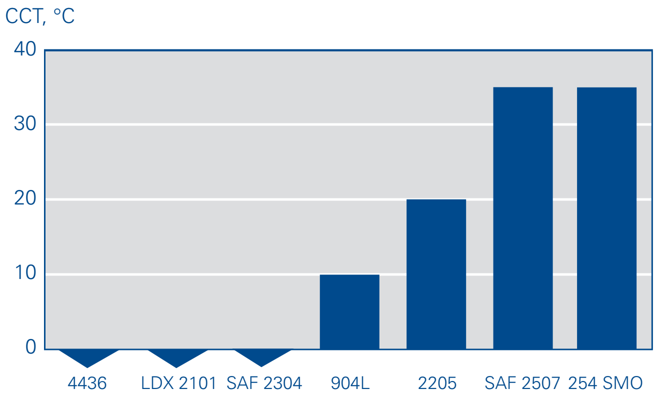

Fig. 7. Typical critical crevice corrosion temperature (CCT) in 6% $FeCl_3$ + 1% according to ASTM G48 Method F. Test surfaces dry ground to 120 mesh.

Stress corrosion cracking

Standard austenitic stainless steel can be attacked by stress corrosion cracking (SCC) in a chloride environment at high temperatures. Stainless steels of the duplex type, are much less sensitive to this type of corrosion, due to a continuous ferritic phase.

Different methods are used to rank the different grades with regard to their resistance to SCC. The result can vary depending on the method and testing environment. The resistance to stress corrosion cracking in a chloride solution under strong evaporative conditions can be determined according to the drop evaporation method. This means that a salt solution is allowed to slowly drip onto a heated specimen, while it is being subjected to tensile stress.
By this method the threshold value is determined for the maximum relative stress not resulting in rupture after 500 hours testing at 100°C. The threshold value is usually expressed as a percentage of the proof strength of the steel at 200°C. Figure 8 shows the results of such a test. It is evident that duplex steels are superior to steels of the 4436 type.

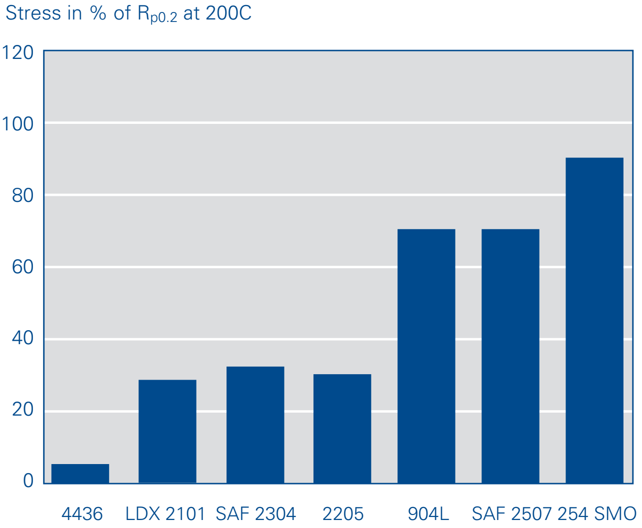

Fig. 8. Threshold values for the relative stress leading to rupture after up to 500 h under strong evaporative conditions. (LDX 2101 indicative value only)

Sulphide stress corrosion cracking

In the presence of hydrogen sulphide and chlorides the risk of stress corrosion cracking increases at lower temperatures. Such environments can exist, for example, in boreholes for oil and gas wells. Steel of the 2205 and SAF 2507 types have demonstrated good resistance, while 13% chromium steels have shown a tendency towards stress corrosion cracking. However, caution should be observed regarding conditions with high partial pressure of hydrogen sulphide and where the steel is subjected to high internal stress.

2205 and SAF 2507 are both approved materials according to NACE MR0175 "Standard Material Requirements – Metals for Sulfide Stress Cracking and Stress Corrosion Cracking Resistance in Sour Oilfield Environments"

For 2205 is stated that "Wrought and cast duplex stainless steel products in the solution-annealed and quenched condition with 30<PREN<40 (>1.5% Mo) are acceptable for use to a maximum temperature of 232°C (450°F) and a maximum H_2S partial pressure of 10 kPa abs (1.5 psia)."

The corresponding conditions for SAF 2507 are that "Wrought and cast duplex stainless steel products in the solution-annealed and quenched condition with a PREN of 40<PREN≤45 are acceptable for use to a maximum temperature of 232°C (450°F) and a maximum H_2S partial pressure of 20 kPa abs (3 psia)."

Corrosion fatigue

The combination of high mechanical strength and very good resistance to corrosion gives duplex steels a high corrosion fatigue strength. S-N curves for 2205 and 4436 in synthetic seawater are shown in Figure 9. The corrosion fatigue strength of 2205 is considerably higher than that of 4436.

Intercrystalline corrosion

Due to the duplex microstructure and low carbon content, these steels have very good resistance to intercrystalline corrosion. The composition of the steel ensures that austenite is reformed in the heat-affected zone after welding. The risk of undesirable precipitation of carbides and nitrides in the grain boundaries is thus minimised.

Erosion corrosion

Stainless steel in general offers good resistance to erosion corrosion. Duplex grades are especially good thanks to their combination of high surface hardness and good corrosion resistance. Examples of applications where this is beneficial are systems subjected to particles causing hard wear e.g. pipe systems containing water with sand or salt crystals.

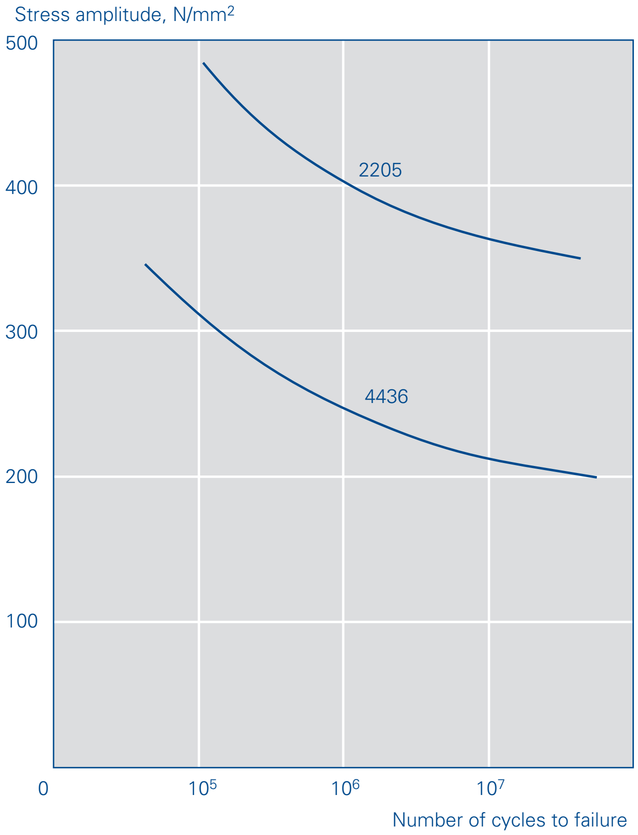

Fig. 9. Corrosion fatigue of stainless steel in synthetic seawater. Rotating bending test, 1500 r/min, with smooth specimens from 15 mm plate.

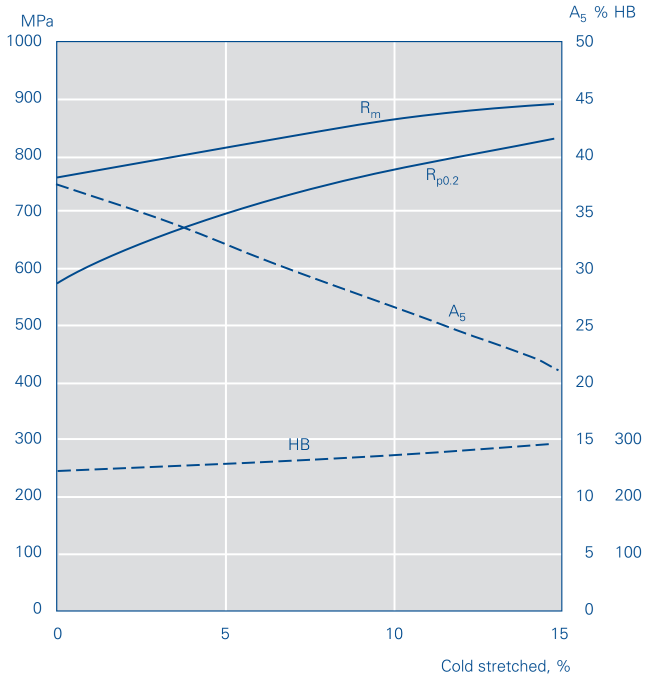

Fig. 10. Mechanical properties of LDX 2101 after cold deformation.

Fabrication

Hot forming

Hot working is performed at the temperatures illustrated in Table 7. It should, however, be observed that the strength of the duplex materials is low at high temperatures. Hot working should normally be followed by quench annealing.

Characteristic temperatures, °C Table 7

	LDX 2101	SAF 2304	2205	SAF 2507
Hot forming	1100-900	1100-900	1150-950	1200-1025
Quench annealing	1020-1080	950-1050	1020-1100	1040-1120
Stress relief annealing	1020-1080	950-1050	1020-1100	1040-1120

Cold forming

Due to the high proof strength of duplex material, greater working forces than those required for austenitic steel are usually needed for cold forming of duplex steel. Figures 10 and 12 show diagrams of the work hardening of LDX 2101, SAF 2304 and 2205 respectively.

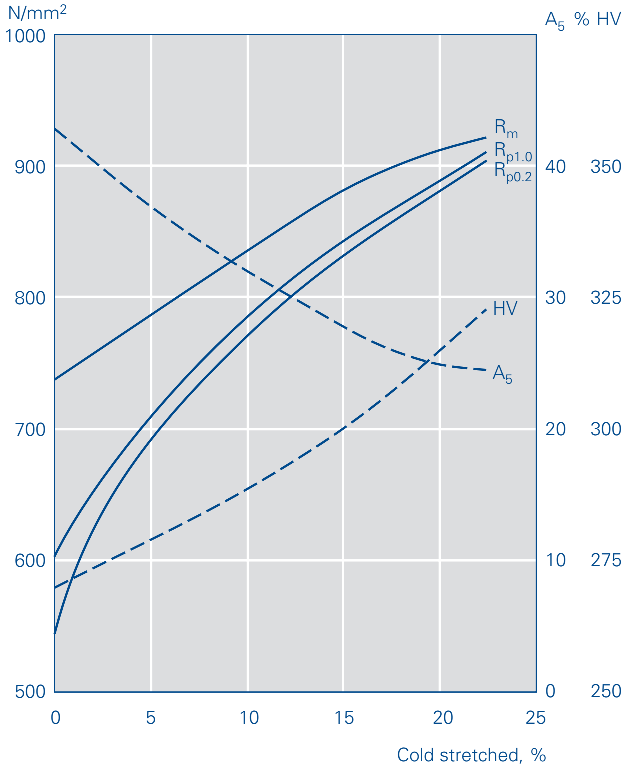

Fig. 11. Mechanical properties of SAF 2304 after cold working.

Duplex steels are suitable for most forming operations used in stainless steel fabrication. However, due to the higher mechanical strength and lower toughness, operations such as deep drawing, stretch forming and spinning are more difficult to perform than with austenitic steel. The high strength of the duplex grades, may cause a relatively high spring back.

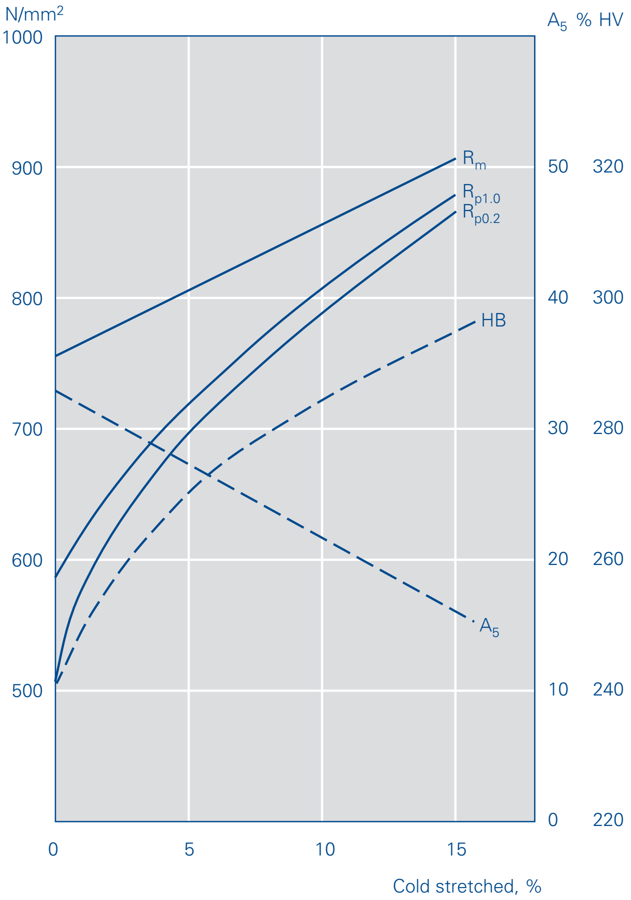

Fig. 13. Mechanical properties of 2205 after cold working.

Heat treatment

Heat treatment is advisable at certain temperatures, as illustrated in Table 8, with subsequent rapid cooling in water or air. This treatment applies for both solution annealing and stress relieving. The latter can in special cases be done at 500-550°C. Further information concerning these operations is available from Outokumpu Stainless.

Machining

Duplex steels are generally more difficult to machine than conventional austenitic stainless steel such as 4436, due to the higher hardness. However LDX 2101 has shown excellent machining properties.

The machinability can be illustrated by a machinability index, as illustrated in Figure 12. This index, which increases with improved machinability, is based on a combination of test data from several different machining operations. It provides a good description of machinability in relation to 4436. Note, however, that the machinability index does not describe the relative difficulty between high-speed steel and carbide tools. For further information contact Avesta Research Centre.

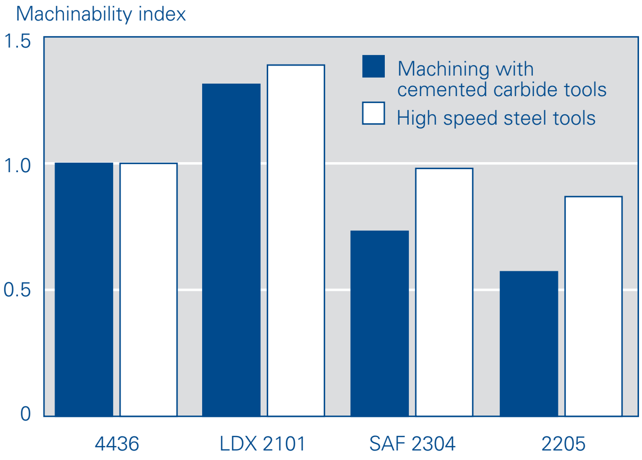

Fig. 14. Machinability index for duplex and some other stainless steels.

Welding

Duplex steels generally have good weldability and can be welded using most of the welding methods used for stainless steel:

- Shielded metal arc welding (SMAW)
- Gas tungsten arc welding TIG (GTAW)
- Gas metal arc welding MIG (GMAW)
- Flux-cored arc welding (FCW)
- Plasma arc welding (PAW)
- Submerged arc welding (SAW)

Due to the balanced composition, the heat-affected zone obtains a sufficiently high content of austenite to avoid the risk of localised corrosion. The individual duplex steels have slightly different welding characteristics. For more detailed information regarding the welding of individual grades, please refer to the relevant welding leaflet issued by Avesta Welding. The following general instructions should be followed:

- The material should be welded without preheating.
- The material should be allowed to cool between passes, preferably to below 150°C.
- To obtain good weld metal properties in as welded condition, filler material shall be used. For LDX 2101 reasonably good properties can be obtained also without filler.
- The recommended arc energy should be kept within certain limits to achieve a good balance between ferrite and austenite in the weld. The heat input should be adapted to the steel grade and be adjusted in proportion to the thickness of the material to be welded.
- Post-weld annealing after welding with filler is not necessary. In cases where heat treatment is considered, e.g., for stress relieving, it should be carried out in accordance with the temperatures stated in Table 8.
- To ensure optimum pitting resistance when using GTAW and PAW methods, an addition of nitrogen in the shielding/purging gas is recommended.

Avesta Welding AB manufactures specially adapted welding consumables for duplex steels in the form of covered welding electrodes, flux-cored welding wire, MIG and TIG wires and wire for submerged arc welding (Table 8). These filler metals ensure weld properties comparable to those of the parent metal.

Further information concerning the welding of duplex steels is available in Avesta Welding's special leaflets "How to weld Duplex stainless Steel.

Welding consumables Table 8

Product form	Designation		Typical composition, %					Ferrite
	Avesta	AWS	C	Cr	Ni	Mo	N	FNA
Welding of SAF 2304 and LDX 2101								
Electrode	2304 AC/DC	–	0.02	24.0	9.0	–	0.12	30
Wire	2304	_	0.02	23.0	7.0	–	0.14	40
Welding of 2205, SAF 2304 and LDX 2101								
Electrode	2205 AC/DC	E 2209-17	0.02	23.0	9.5	3.0	0.15	30
	2205 PW	E 2209-17	0.02	22.5	9.5	3.1	0.15	30
	2205 Basic	E 2209-15	0.02	23.0	9.5	3.1	0.15	30
Wire	2205	–	0.02	22.5	8.0	3.0	0.16	45
Flux cored wire	2205	E 2209-T1-1	0.03	23.0	9.0	3.1	0.15	35
Welding of SAF 2507								
Electrode	2507/P100		0.03	25.0	9.5	3.6	0.22	30
Wire	2507/P100		0.02	25.0	9.5	4.0	0.25	35

Products

Table 9

Hot rolled plate, sheet and strip	Dimensions according to Outokumpu Stainless product program.
Cold rolled sheet and strip	Dimensions according to Outokumpu Stainless product program.
Bars and forging	Dimensions according to Outokumpu Stainless product program.
Tube, Pipe and Fittings	Supplied by Outokumpu Stainless Tubular Products.
Welding consumables	Filler material in the form of covered electrodes of AC/DC type, MIG, TIG, FCW and SAW wire and also welding flux are supplied by Avesta Welding AB, Avesta.

Material Standards

Table 10

EN 10028-7	Flat products for pressure purposes – Stainless steels
EN 10088-2	Stainless steels – Corrosion resisting sheet/plate/strip for general and construction purposes
EN 10088-3	Stainless steels – Corrosion resisting semi-finished products/bars/rods/wire/sections for general and construction purposes
EN 10217-7	Welded steel tubes for pressure purposes – Stainless steel tubes
EN 10272	Stainless steel bars for pressure purposes
EN 10296-2	Welded circular steel tubes for mechanical and general engineering purposes - Stanless Steel tubes
ASTM A182 / ASME SA-182	Forged or rolled alloy-steel pipe flanges, forged fittings etc for high temperature service
ASTM A240 / ASME SA-240	Heat-resisting Cr and Cr-Ni stainless steel plate/sheet/strip for pressure purposes
ASTM A276	Stainless and heat-resisting steel bars/shapes
ASTM A479 / ASME SA-479	Stainless steel bars for boilers and other pressure vessels
ASTM A789 / ASME SA-789	Seamless and welded duplex stainless steel tubing for general purposes
ASTM A790 / ASME SA-790	Seamless and welded duplex stainless steel pipe
ASTM A815 / ASME SA-815	Wrought ferritic, duplex, martensitic stainless steel piping fittings
ASTM A928	Duplex stainless steel pipe welded with addition of filler metal
VdTÜV WB 418	Ferritisch-austenitischer Walz- und Schmiedestahl, 1.4462
VdTÜV WB 496	Ferritisch-austenitischer Walz- und Schmiedestahl, 1.4362
VdTÜV 508	Ferritisch-austenitischer Walz- und Schmiedestahl, 1.4410
NACE MR0175	Sulphide stress cracking resistant material for oil field equipment
Norsok M-CR 630, MDS D45	
ASME Boiler and Pressure Vessel Code Case 2418	21Cr-5Mn-1.5Ni-Cu-N (UNS S32101), Austenitic-Ferritic Duplex Stainless Steel Section VIII, Division 1

Outokumpu Stainless 2205 corresponds in American Standards to two different steel designations; UNS S31803 and UNS S32205. The latter has closer tolerance limits for some alloying elements to further optimise properties such as corrosion resistance and strength.

SAF 2304® and SAF 2507® are trademarks owned by Sandvik AB

Outokumpu is a dynamic metals and technology group. Focusing on our core competences, that is, extensive knowledge of metals and metals processing, we aim to be leaders in all of our key business'. Customers in a wide range of industries use our metals, metal products, technology and services worldwide.

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