Duplex Stainless Steel

OUTO KUMPU

Steel grades

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

Characteristic properties

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

Applications

- Pulp and paper industry
- Desalination plants
- Flue-gas cleaning
- Cargo tanks and pipe systems in chemical tankers
- Seawater systems
- Firewalls and blast walls on offshore platforms
- Bridges
- Components for structural design
- Storage tanks
- Pressure vessels
- Heat exchangers
- Water heaters
- Rotors, impellers and shafts

General characteristics

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

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

Chemical composition

The typical chemical compositions of Outokumpu grades are shown in table 1. 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	Outokumpu steel name	International steel No		Chemical composition, % Typical values						National steel designations, superseded by EN			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
Duplex	LDX 2101®	1.4162	S32101	0.03	0.22	21	1.5	0.3	5Mn	–	–	–	–
Duplex	2304	1.4362	S32304	0.02	0.10	23	4.8	0.3	–	–	1.4362	Z3 CN 23-04 Az	2327
Duplex	2205	1.4462	S32205*	0.02	0.17	22	5.7	3.1	–	318S13	1.4462	Z3 CND 22-05 Az	2377
Duplex	4501	1.4501	S32760	0.02	0.25	25	7,0	3.8	W,Cu	–	–	–	–
Duplex	2507	1.4410	S32750	0.02	0.27	25	7,0	4,0	–	–	–	Z3 CND 25-06 Az	2328
Austenitic	4307	1.4307	304L	0.02	–	18	8.3	–	–	304S11	1.4307	Z3 CN 18-10	2353
Austenitic	4404	1.4404	316L	0.02	–	17	11	2.1	–	316S11	1.4404	Z3 CND 17-11-02	2348
Austenitic	904L	1.4539	N08904	0.01	–	20	25	4.3	1.5Cu	904S13	1.4539	Z2 NCDU 25-20	2562
Austenitic	254 SMO®	1.4547	S31254	0.01	0.20	20	18	6.1	Cu	–	–	–	2378

* 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.

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 at heat treatment of thick sections, especially if the cooling is slow.

Figure 1 illustrates the relation between time and temperature that leads to a reduction of the impact toughness with 50%.

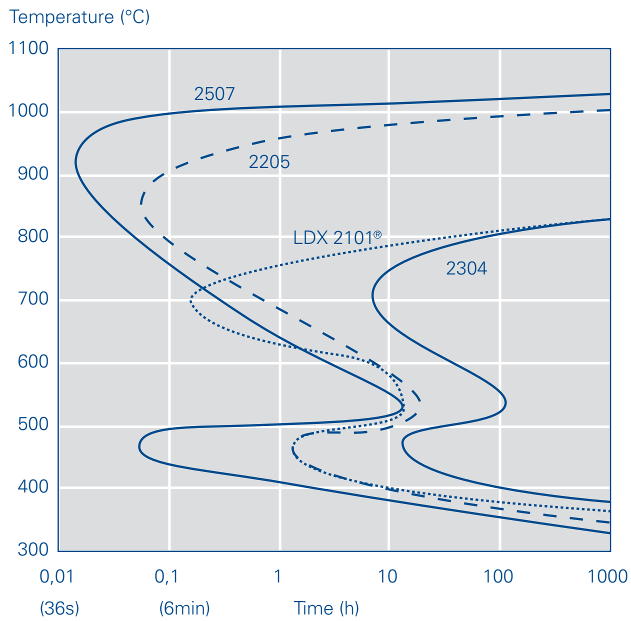

Fig. 1. Curves for reduction of impact toughness to 50% compared to solution annealed condition.

Mechanical properties

Tables 2-4 show the mechanical properties for flat rolled products. Data according to EN 10088 and EN 10028 when applicable. LDX 2101® is not yet listed in EN 10088, data corresponds to ASTM A240 and to an internal standard, AM 611. The allowable design values may vary between product forms. The appropriate values are given in the relevant specifications.

Mechanical properties at 20°C — Table 2

			Minimum values, according to EN 10088			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
2304								
Proof strength	$R_{p0.2}$	MPa	400	400	450	450	520	545
Tensile strength	R_m	MPa	630	650	650	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	500	510	620	635
Tensile strength	R_m	MPa	640	700	700	750	820	835
Elongation	A_5	%	25	25	20	35	35	35
Hardness	HB					250	250	250
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	20	20	35	30	33
Hardness	HB					250	265	255

P = hot rolled plate. H = hot rolled strip. C = cold rolled coil and strip.
* Mechanical properties according to ASTM A240 and to internal standard, AM 611.

Impact toughness.
Minimum values according to EN 10028, transverse direction, J Table 3

	LDX 2101®*	2304	2205	2507
20°C	60	60	60	60
-40°C	27	40	40	40

* Values from internal standard, AM 611

Tensile properties at elevated temperatures.
Minimum values according to EN 10028, MPa Table 4

	LDX 2101®*		2304		2205		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

* Values for hot rolled and cold rolled strip according to AM 611

Fatigue

The high tensile strength of duplex steels also implies high fatigue strength. Table 5 shows the result of pulsating tensile fatigue tests (R= σmin/σmax= 0.1) in air at room temperature. The fatigue strength has been evaluated at 2 million cycles and a 50% probability of rupture. The test was made using round polished bars. 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®	2304	2205	2507	4404
$R_{p0.2}$	478	446	497	565	280
R_m	696	689	767	802	578
Fatigue strength	500	450	510	550	274

Physical properties

Physical data according to EN 10088 apply for all our duplex steels, see Table 6.

Typical values Table 6

		20°C	100°C	200°C	300°C
Density	g/cm³	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 provide a wide range of corrosion resistance in various environments. For a more detailed description of their resistance, see our Corrosion Handbook. A brief description follows below regarding their resistance in different types of environments.

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, in most cases, a better resistance than 4307 and in some cases as good as 4404. 2304 is in most cases equivalent to 4404, while the other more highly-alloyed duplex steels show even better resistance.

Sulphuric acid

The isocorrosion diagram in sulphuric acid is shown in Figure 2. In sulphuric acid contaminated by chloride ions, 2205® shows much better resistance than 4404 and a similar resistance to that of 904L, Figure 3.

Hydrochloric acid

Stainless steel grades such as 4307 and 4404 have very limited use in hydrochloric acid because of the risk of uniform and localised corrosion. High-alloyed steels such as 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 in the isocorrosion diagram but crevices should be avoided.

Nitric Acid

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

Pitting and crevice corrosion

The resistance to pitting and crevice corrosion increases with the content of chromium, molybdenum and nitrogen in the steel. This is often illustrated by the pitting resistance equivalent (PRE) for the material, which can be calculated by using the formula: PRE = %Cr + 3,3x%Mo + 16x%N. PRE values given for different grades are presented in table 7. Due to their different alloying levels, the four duplex steels show considerable differences in this respect. LDX 2101® has a resistance approaching that of 4404, 2304 is on a level with conventional molybdenum-alloyed steels of the 4404 type, while 2205 is on a level with 904L and 2507 with 6Mo steels.
The PRE value can be used for a rough comparison between different materials. A much more reliable way of ranking steels is according to the critical pitting temperature

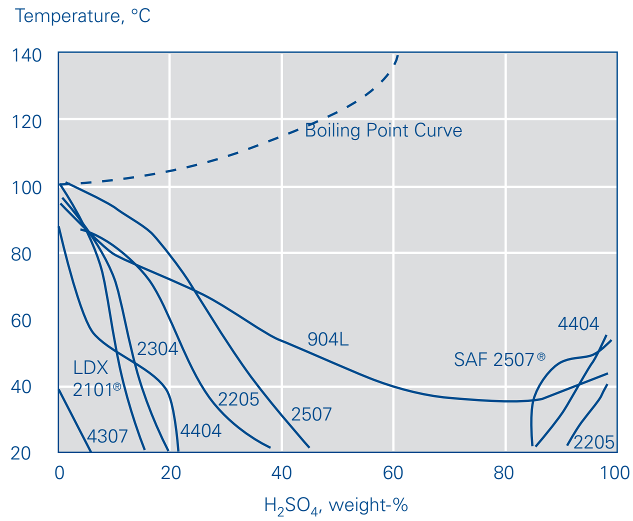

Fig. 2. Isocorrosion curves, 0.1 mm/year, in sulphuric acid.

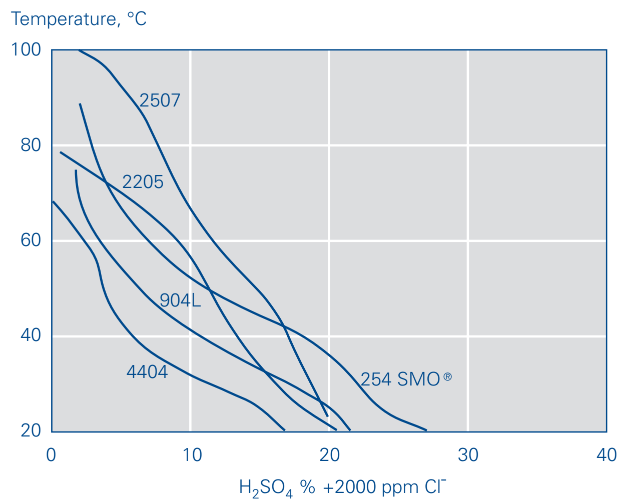

Fig. 3. Isocorrosion curves, 0,1 mm/year, in sulphuric acid containing 2000 ppm chloride ions.

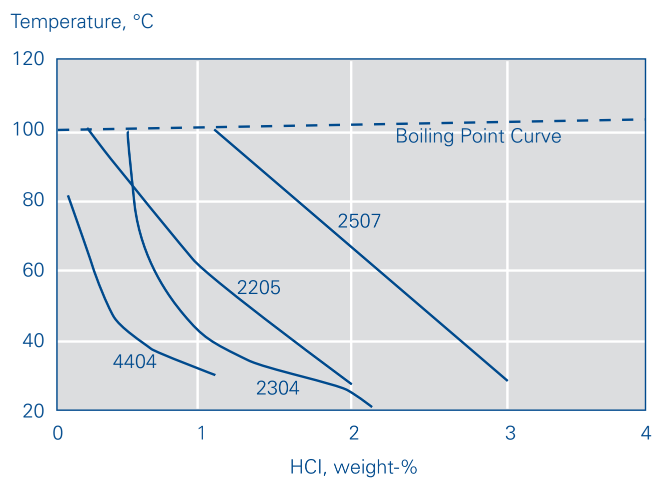

Fig. 4. Isocorrosion curves 0.1mm/year, in hydrochloric acid.

(CPT). There are several methods available to measure CPT. The electrochemical method, used by Outokumpu 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 5. The actual value of the as delivered surface may differ between product forms.
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 6. Different products and different surface finishes, e.g. mill finish surfaces, may show CCT values that differ from the values given in the figure.

PRE values for different austenitic and duplex grades. Table 7

Steel grade	PRE
4307	18
4404	24
LDX 2101®	26
2304	26
904L	34
2205	35
254 SMO®	43
2507	43

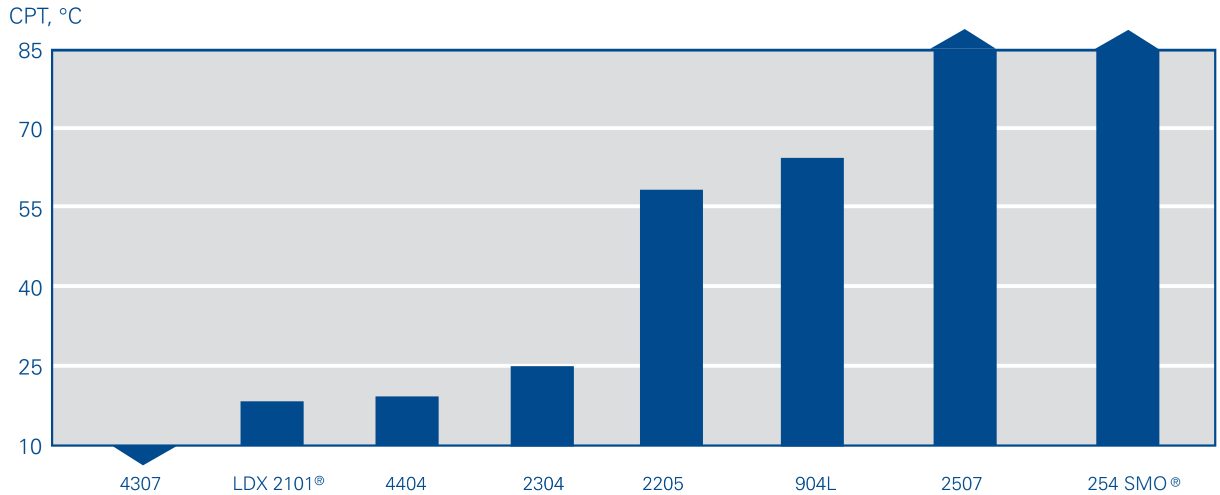

Fig. 5. Typical critical pitting corrosion temperatures (CPT) in 1M NaCl measured according to ASTM G150 using the Avesta Cell. Test surfaces wet ground to 320 mesh. CPT varies with product form and surface finish.

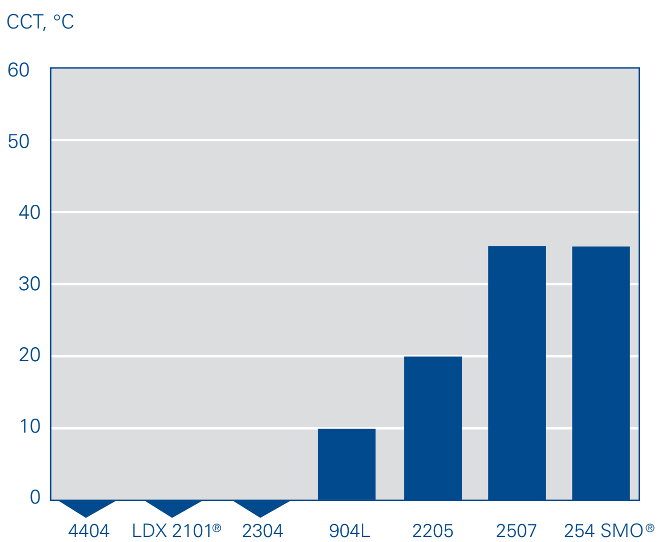

Fig. 6. Typical critical crevice corrosion temperature (CCT) according to ASTM G48 Method F. Test surfaces dry ground to 120 mesh. CCT varies with product form and surface finish

Stress corrosion cracking

Conventional austenitic stainless steel can be attacked by stress corrosion cracking (SCC) in chloride environments at elevated temperatures. Stainless steels of the duplex type are less susceptible to this type of corrosion.
Different methods are used to rank stainless steel grades with regard to their resistance to SCC. The results can vary depending on the method and testing environment. The resistance to stress corrosion cracking in a chloride solution under 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 7 shows the results of such a test. It is evident that duplex steels are superior to conventional austenitic stainless steel, such as 4307 and 4404.

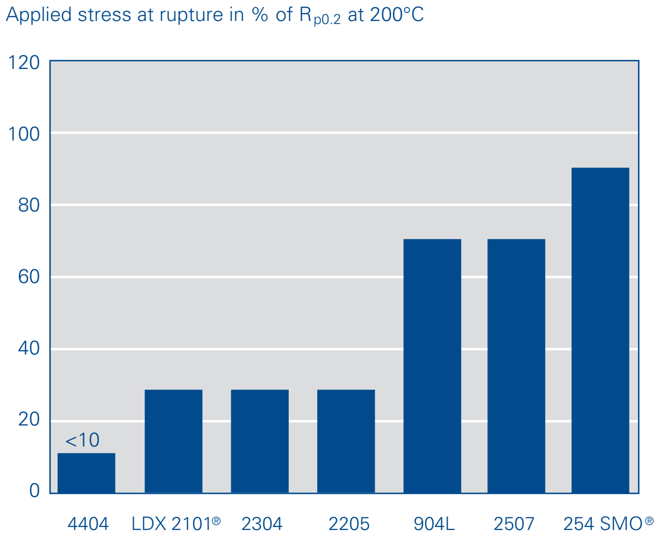

Fig. 7. Typical threshold stresses determined using the drop evaporation test.

Sulphide induced stress corrosion cracking

In the presence of hydrogen sulphide and chlorides the risk of stress corrosion cracking, at low temperatures, increases. Such environments can exist, for example, in boreholes for oil and gas wells. Duplex grades, such as 2205 and 2507 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 2507 are both approved materials according to NACE MR0175 / ISO 1515 Petroleum and natural gas industries - Materials for use in H_2S-containing environments in oil and gas production.

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 4404 in synthetic seawater are shown in Figure 8. The corrosion fatigue strength of 2205 is considerably higher than that of 4404.

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.

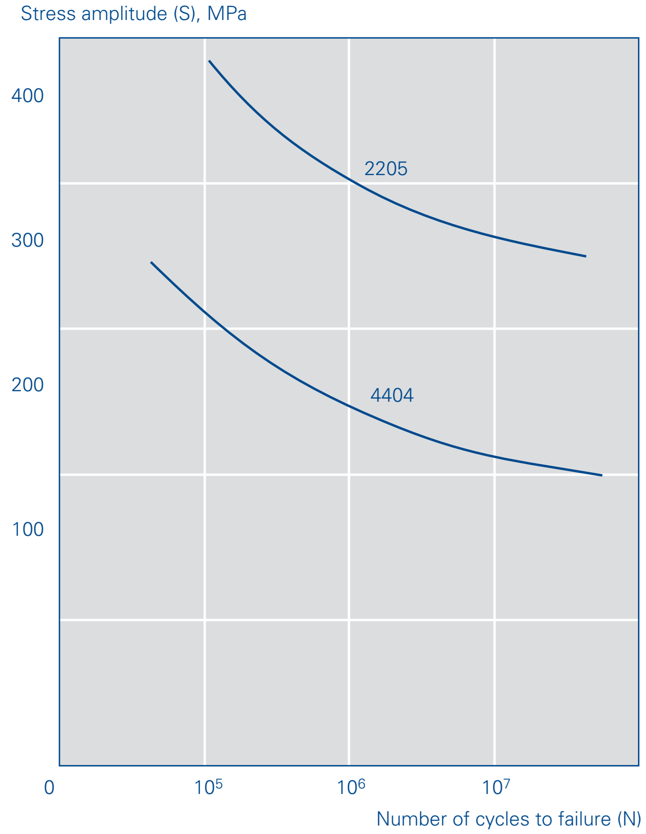

Fig. 8. Corrosion fatigue of stainless steel in synthetic seawater. Rotating bending test, 1500 r/min, with smooth specimens from 15 mm plate.

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.

Galvanic Corrosion

Galvanic corrosion can occur when two dissimilar metals are connected. The noblest material is protected while the less noble material is more severely attacked. As long as the duplex stainless steels are passive they are, in most environments, nobler than other metallic construction materials, meaning that the stainless steel is protected while the corrosion rate of e.g. carbon steel is increased.

Galvanic corrosion does not occur between different grades of stainless steels as long as both grades are passive.

Fabrication

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 demanding to perform than with austenitic steel. The high strength of the duplex grades, may cause a relatively high spring back.

Hot forming

Hot working is performed at the temperatures illustrated in Table 8. It should, however, be observed that the strength of the duplex materials is low at high temperatures and fabricated components require support during fabriction. Hot working should normally be followed by quench annealing.

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 9 to 11 show diagrams of the work hardening of LDX 2101®, 2304 and 2205 respectively.

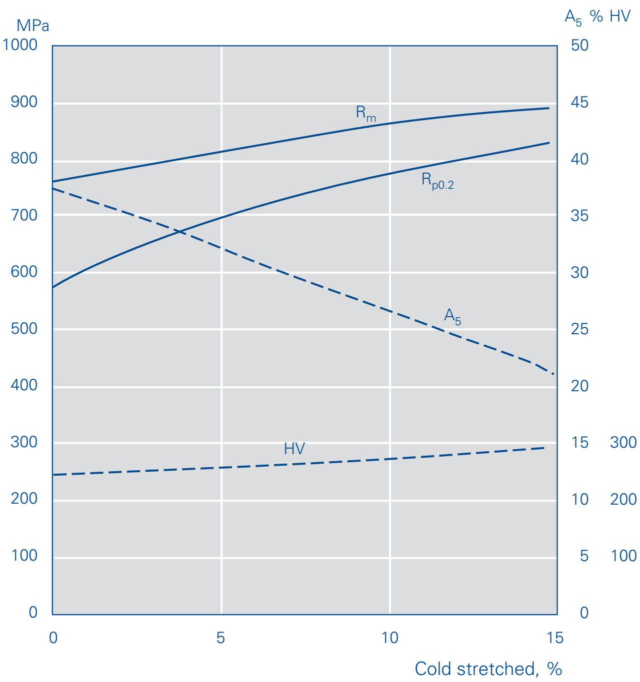

Fig. 9. Mechanical properties of LDX 2101® after cold working.

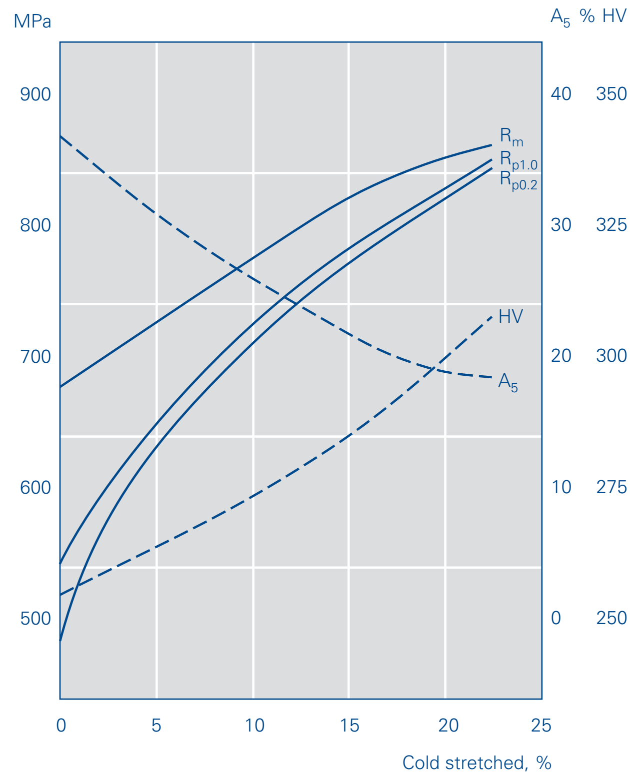

Fig. 10. Mechanical properties of 2304 after cold working.

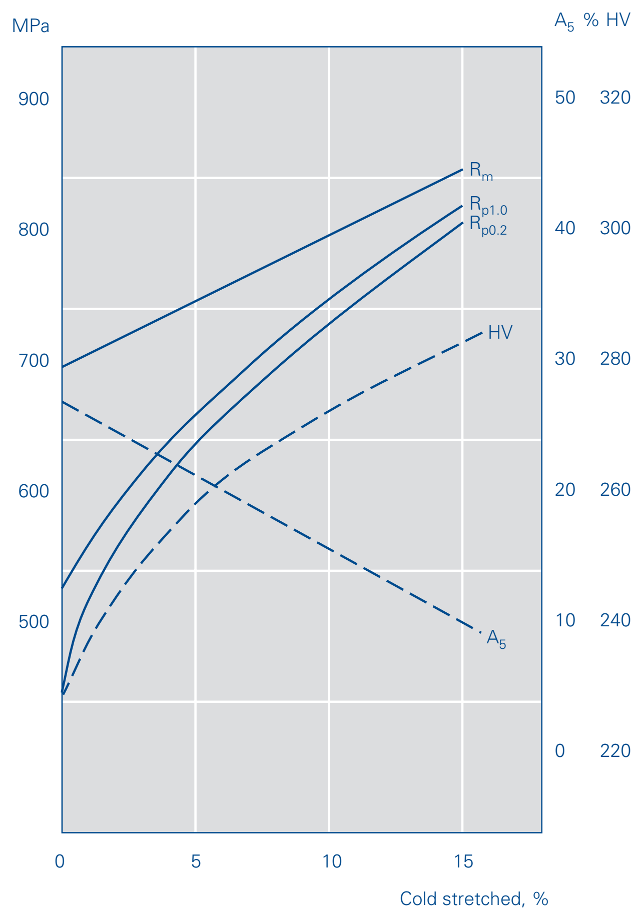

Fig. 11. Mechanical properties of 2205 after cold working.

Heat treatment

Temperatures suitable for heat treatment are presented in Table 8. The heat treatment should be followed by 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.

Characteristic temperatures, °C Table 8

	LDX 2101®	2304	2205	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

See also "Welding"

Machining

Duplex steels are generally more demanding to machine than conventional austenitic stainless steel such as 4404, 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 4404. Note, however, that the machinability index does not describe the relative performance between high-speed steel and carbide tools. For further information contact Outokumpu.

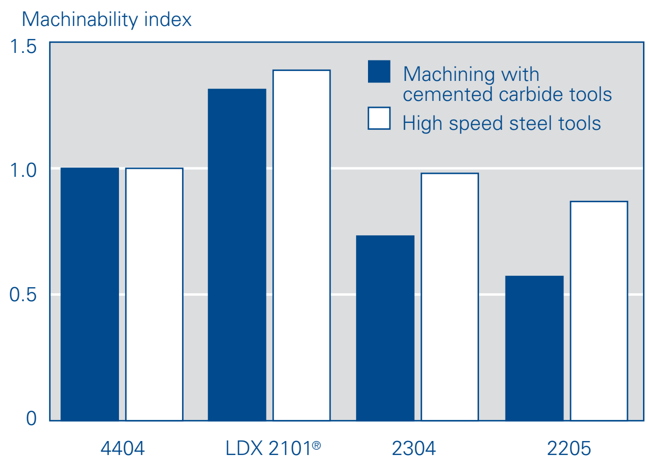

Fig. 12. Machinability index for duplex and some other stainless steels.

Welding

Duplex steels generally have good weldability and can be welded using most of the welding methods used for austenitic 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)
- Others; laser, resistance welding, high frequence welding

Due to the balanced composition, the heat-affected zone obtains a sufficiently high content of austenite to maintain a good resistance to localised corrosion.The individual duplex steels have slightly different welding characteristics. For more detailed information regarding the welding of individual grades, contact Outokumpu. 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, but with the minimum temperature increased with 30-50°C to secure full dissolution of intermetallic phase in the the weld metal.
- To ensure optimum pitting resistance when using GTAW and PAW methods, an addition of nitrogen in the shielding/purging gas is recommended.

Post Fabrication treatment

In order to restore the stainless steel surface and achieve good corrosion resistance after fabrication, it is often necessary to perform a post fabrication treatment.
There are different methods available, both mechanical methods such as brushing, blasting and grinding and chemical methods, e.g. pickling. Which method to apply depend on what consequences the fabrication caused, i.e. what type of imperfections to be removed, but also on requirements with regard to corrosion resistance, hygienic demands and aesthetic appearance. For more information contact Outokumpu.

Welding consumables Table 9

Product form	ISO Designation	Typical composition, % C	Cr	Ni	Mo	N	Ferrite FNA
Welding of LDX 2101®							
Covered electrode	LDX 2101®*	0.04	23.5	7.0	0.3	0.14	35
Solid wire (MIG, TIG, SAW)	LDX 2101®*	0.03	23.0	7.0	0.3	0.14	40
Flux cored wire	LDX 2101®*	0.03	24.0	9.0	0.6	0.14	35
Welding of SAF 2304							
Covered electrodes	2304*	0.02	24.5	9.0	0.2	0.12	30
Solid wire	2304*	0.02	23.5	7.5	<0.5	0.14	40
Flux cored wire	2304*	0.03	24.5	9.0	0.2	0.12	35
Welding of 2205							
Covered electrodes (ISO 3581)	22 9 3 N L R	0.02	23.0	9.5	3.0	0.15	30
Solid wire (ISO14343)	22 9 3 N L	0.02	23.0	8.5	3.1	0.17	45
Flux cored wire (ISO 17633)	22 9 3 N L	0.03	23.0	9.0	3.2	0.13	45
Welding of 2507							
Covered electrode (ISO 3581)	25 9 4 N L R	0.03	25.5	10.0	3.6	0.23	30
Solid wire (ISO 14343)	25 9 4 N L	0.02	25.0	9.5	4.0	0.25	35

* Avesta Welding Designation. Filler for 2205 can be used for most applications

Products

Table 10

Hot rolled plate, sheet and strip	Dimensions according to Outokumpu product program.
Cold rolled sheet and strip	Dimensions according to Outokumpu product program.
Bars and forging	Dimensions according to Outokumpu product program.
Tube, Pipe and Fittings	Dimensions according to Outokumpu product program.

See also www.outokumpu.com/prodprog

Material Standards

Table 11

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 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, the properties described in this datasheet corresponds to UNS S32205.

1008EN-GB:6. Centrumtryck AB, Avesta, Sweden. May 2008.

Outokumpu is a global leader in stainless steel. Our vision is to be the undisputed number one in stainless, with success based on operational exellence. Customers in a wide range of industries use our stainless steel and services worldwide. Being fully recyclable, maintance-free, as well as very strong and durable material, stainless steel is one of the key building blocks for sustainable future.

What makes Outokumpu special is total customer focus, all the way, from R&D to delivery. You have the idea. We offer world-class stainless steel, technical know-how and support. We activate your ideas. (www.outokumpu.com)

Outokumpu Stainless AB, Avesta Research Centre
Box 74, SE-774 22 Avesta, Sweden
Tel. +46 (0)226 810 00, Fax +46 (0)226 810 77
research.stainless@outokumpu.com