Duplex Stainless Steel LDX 2404™

Steel grade

Outokumpu	EN	ASTM/UNS
LDX 2404™	1.4662	S82441

Characteristic properties

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

Application areas

- Storage tanks
- Architectural applications
- Structural components
- Piping systems
- Boilers and water heaters
- Pulp & Paper
- Oil & Gas
- Energy
- Water treatment and desalination
- Process industry

General characteristics

LDX 2404™ is a molybdenum-containing duplex stainless steel with high contents of chromium and nitrogen. The grade combines a higher mechanical strength than for other common duplex grades with a generally high corrosion resistance. These characteristics make LDX 2404™ well suited for optimal designs with respect to strength, reduced maintenance, durability and long-term cost efficiency.
As for all duplex grades the maximum service temperature is restricted to 250 or 325°C according to EN10028-7 or ASME II-D 2007 respectively.

Chemical composition

The typical chemical composition of LDX 2404™ is shown in Table 1.

Microstructure

The balanced chemical composition of LDX 2404™results in a microstructure containing approximately equal amounts of ferrite and austenite after annealing. Cold rolled material can be annealed as low as 1000°C whereas hot rolled material should be annealed in the temperature range 1080-1120°C. Due to the lower alloy content, mainly molybdenum, the precipitation of undesirable intermetallic phases is more sluggish than for conventional comparable duplex grades, like 2205. The high nitrogen content results in a rapid reformation of austenite when welding, which improves weld toughness.

Mechanical properties

LDX 2404™ has high mechanical strength. In Table 2, minimum and typical values for the grade are presented. The mechanical properties at elevated temperatures are shown in Table 3.

Chemical composition. Table 1

Outokumpu steel name	International steel No		Chemical composition, % by wt Typical values						National steel designations, superseded by EN			
	EN	ASTM/UNS	C	N	Cr	Ni	Mo	Others	BS	DIN	NF	SS
LDX 2101®	1.4162	S32101	0.03	0.22	21.5	1.5	0.3	5Mn	–	–	–	–
2304	1.4362	S32304	0.02	0.10	23	4.8	0.3	–	–	1.4460	Z3 CN 23-04 Az	2327
LDX 2404™	**1.4662**	**S82441**	**0.02**	**0.27**	**24**	**3.6**	**1.6**	**3Mn**	**–**	**–**	**–**	**–**
2205	1.4462	S32205	0.02	0.17	22	5.7	3.1	–	318S13	1.4462	Z3 CND 22-05 Az	2377
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	904L	0.01	–	20	25	4.3	1.5Cu	904S13	1.4539	Z2 NCDU 25-20	2562

Mechanical properties at 20°C, according to internal standard AM641. Table 2

			Minimum values			Typical values*		
			P	H	C	P (15 mm)	H (4 mm)	C (1 mm)
Proof strength	$R_{p0.2}$	MPa	480	550	550	540	620	640
Tensile strength	R_m	MPa	680	750	750	750	800	850
Elongation	A_5	%	25	25	25/20[2]	33	32	30
Impact toughness[1])	KV	J	60	80	80	130		
Hardness	HB	max	290	290	290	230		

* Typical values are in the process of being established
[1]) Refer to full size Charpy-V specimens performed on gauges >10 mm. [2]) Refers to A_{80} for gauges less than 3.0 mm. P = Hot rolled plate, H = Hot rolled coil, C = Cold rolled plate and sheet.

Tensile properties at elevated temperatures. Table 3

High temperature strength			Temperature, °C					
			50	100	150	200	300	350
Minimum values	$R_{p0.2}$	MPa	445	385	345	325	300	300
	R_m	MPa	660	615	590	575	555	555

Fatigue

The high tensile strength of LDX 2404™ also implies high fatigue strength. The fatigue strength at R=0.1 evaluated at 2 million cycles for 95% probability of survival has been determined to be in excess of 500 MPa for cold rolled material. Correction factors for surface roughness, notches, welds, etc., are always required for utilisation of fatigue data.

Physical properties

The physical properties of LDX 2404™ are shown in Table 4.

Physical properties. Table 4

		20°C	100°C	200°C	300°C
Density	x 10^3 kg/m²	7.7			
Modulus of elasticity	GPa	205	(194)	(186)	(180)
Poissons ratio		(0.3)			
Thermal expansion at (20 → T)°C	x 10^3/°C		13.0	13.5	14.0
Thermal conductivity	W/m°C	14.5	16	18	21
Thermal capacity	J/kg°C	(500)			
Electric resistivity	nΩm	(0.80)			

Values within brackets are typical duplex values. Grade specific values are in the process of being established for LDX 2404™.

Corrosion resistance

The corrosion resistance of LDX 2404™ is better than for Cr-Ni-Mo grades such as 4404 and duplex grades such as 2304. The grade is suitable for use in a wide range of applications and environments. A brief description of the resistance to different types of corrosion is given below.

Uniform corrosion

Uniform corrosion is characterized by uniform attack on the steel surface in contact with a corrosive medium. Uniform corrosion data in various solutions based on the widely accepted MTI-1 procedure are shown in Table 5 and Figure 1. The results are presented as the critical temperature where the corrosion rate exceeds 0.127 mm/year in the test solution.

The critical temperatures in the test solutions prescribed by MTI-1. Table 5

Test solution		Concentration [% by wt]	Critical temperature [°C]
Hydrochloric acid	HCl	0.2	>100 (bp)
Hydrochloric acid	HCl	1.0	95p
Hydrochloric acid + ferric chloride	HCl + $FeCl_3$	1.0 + 0.3	50
Sulphuric acid	H_2SO_4	10	75
Sulphuric acid + chlorides	H_2SO_4 + Cl^-	10 + 2000 ppm	35
Sulphuric acid + chlorides + sulphur dioxide	H_2SO_4 + Cl^- + SO_2	10 + 2000 ppm + sat.	25
Sulphuric acid	H_2SO_4	60	<15
Sulphuric acid	H_2SO_4	96	40
Phosphoric acid	H_3PO_4	85	100
Phosphoric acid + hydrofluoric acid	H_3PO_4 + HF	83 + 2	45
WPA 1	[1]		55
WPA 2	[1]		55
Nitric acid	HNO_3	10	>100 (bp)
Nitric acid	HNO_3	65	100
Nitric acid + hydrochloric acid	HNO_3 + HCl	60 + 2	>60
Acetic acid	CH_3COOH	80	>106 (bp)
Acetic acid + acetic anhydride	CH_3COOH + $(CH_3CO)_2O$	50 + 50	90
Formic acid	HCOOH	50	85
Sodium hydroxide	NaOH	50	100

bp = boiling point. p = pitting.
[1]) The WPA 1 (high Cl^-, low F^-) and WPA 2 (low Cl^-, high F^-) solutions were designed to simulate wet process phosphoric acids.

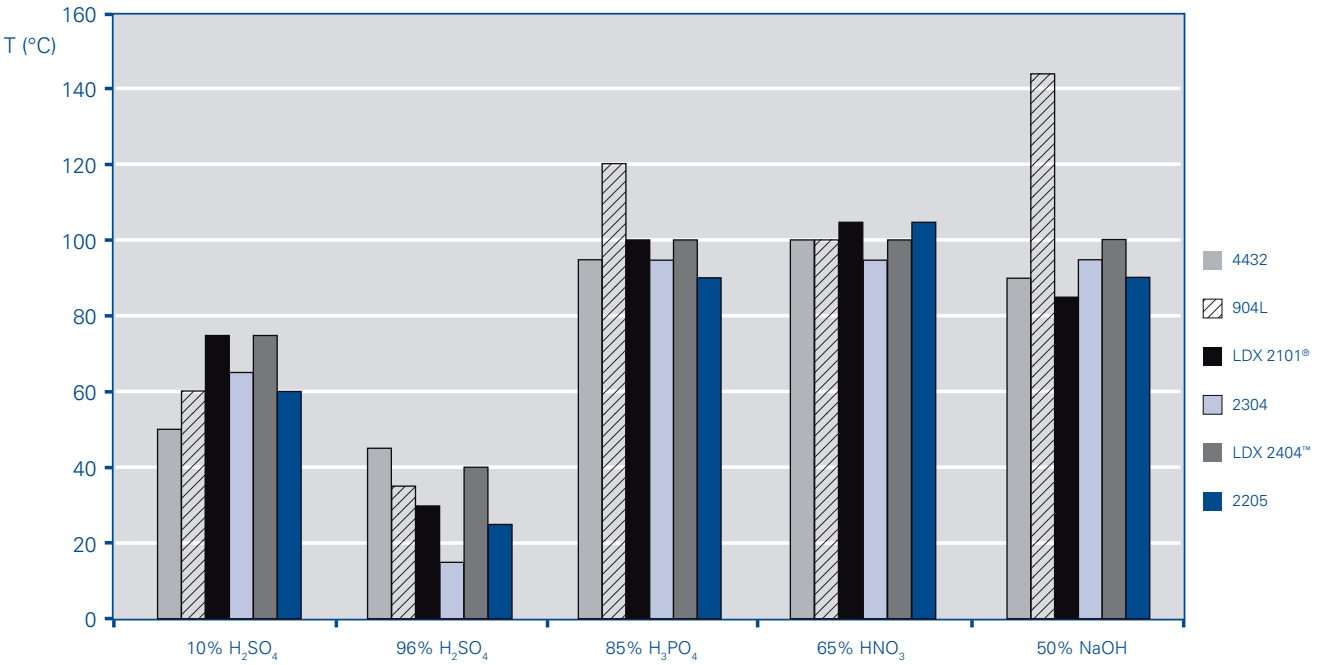

Fig. 1. Critical temperatures in selected test solutions prescribed by MTI-1.

Pitting and crevice corrosion

The resistance to pitting and crevice corrosion is particularly important in chloride-containing environments. The resistance of LDX 2404™ to these types of corrosion is good, due to the high chromium and nitrogen content of this grade and further improved by the addition of molybdenum. One common way to describe the relative corrosion resistance is to use the pitting resistance equivalent, PRE, (%Cr + 3.3 x %Mo + 16 x %N) shown in Table 6.

PRE, Typical values for duplex grades. Table 6

	LDX 2101®	2304	LDX 2404™	2205
PRE	26	26	33	35

The pitting corrosion resistance has been evaluated according to ASTM G 150 using the Avesta Cell, where the critical pitting corrosion temperature, CPT, is determined. The values for LDX 2404™ are compared with other Outokumpu grades in Figure 2.

The crevice corrosion resistance, expressed as the critical crevice corrosion temperature (CCT), has been measured using the ASTM G 48 F method. LDX 2404™ is compared with some other Outokumpu grades in Figure 3.

Atmospheric corrosion

The resistance of a steel to atmospheric corrosion is strongly linked to its resistance to localized corrosion such as pitting and crevice corrosion. Since LDX 2404™ shows good resistance to these types of corrosion, the resistance to atmospheric corrosion is good. Accordingly LDX 2404™ is sufficiently resistant in most environments, including seaside locations. Early results from a marine atmospheric testing station have shown LDX 2404™ to be on a par with 2205.

Stress corrosion cracking

Like all duplex stainless steels, LDX 2404™ shows good resistance to chloride-induced stress corrosion cracking (SCC). Several test methods are used to rank different steel grades with respect to their resistance to SCC. In Table 7 results from immersion tests in NaCl, $CaCl_2$ and $MgCl_2$ (ASTM G 36), and the evaporative method, wick test (ASTM C 692) are summarised.

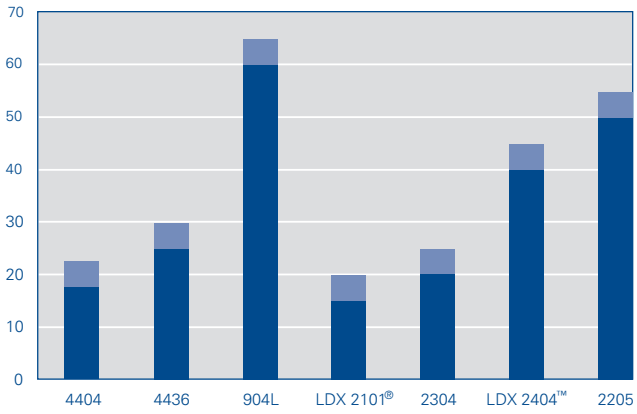

Fig. 2. CPT values according to ASTM G 150 for ground surface (320 mesh) of Outokumpu stainless steel grades.

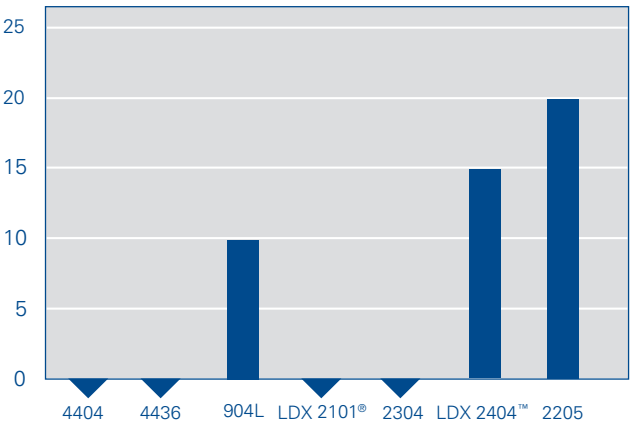

Fig. 3. CCT values according to ASTM G 48 F for ground surface (120 mesh) of Outokumpu stainless steel grades.

Intergranular corrosion

Due to its duplex microstructure LDX 2404™ offers very good resistance to intergranular corrosion. LDX 2404™ passes intergranular corrosion tests according to EN/ISO 3651-2 method A (Strauss Test) and method B (Streicher Test). The result from the intergranular corrosion test ISO 3651-1/ ASTM A 262 practice C (Huey Test) designed to evaluate materials in contact with strongly oxidising agents, e.g. nitric acid, shows better or similar performance for LDX 2404™ compared to 2304.

Results from SCC testing Table 7

Grade	25% NaCl boiling, 107°C U-bend	40% $CaCl_2$ 100°C $R_{p0.2}$ (4-PB)	ASTM G 36 45% $MgCl_2$ 154°C U-bend	ASTM C 692 1500 ppm Cl^- 100°C wick test
LDX 2404™	No SCC	No SCC	SCC	No SCC
2205	No SCC	No SCC	SCC	No SCC
4404	SCC	SCC	SCC	SCC

Fabrication

Hot forming

Hot forming is performed in the temperature range 1120-900°C and should be followed by a solution annealing to restore the original properties. The mechanical strength of the material is low at these high temperatures.

Cold forming

LDX 2404™ is suitable for most forming operations used in stainless steel fabrication. Due to the high proof strength of LDX 2404™, greater working forces than those required for austenitic steel are usually needed for cold forming operations such as deep drawing and spinning. However, in many cases the yield strength can be utilised for down-gauging which reduces the need for larger working forces. The high strength also gives a relatively high springback compared to austenitic grades. Figure 4 shows how mechanical properties, elongation and hardness varies with prior cold working.

Machining

Milling tests show similar or better results than for 2205, but not as good as reported for LDX 2101®.

Heat treatment

LDX 2404™ is solution annealed at 1000-1120°C. Rapid cooling is recommended after annealing to restore the original properties. Support during annealing may be used to avoid shape distortion.

Welding

LDX 2404™ has good weldability and can be welded using the same processes used for other duplex steels. In general the recommendations given for welding of duplex steels also apply for this grade. As the steel is alloyed with nitrogen, it is beneficial to add nitrogen to the shielding gas with GTAW and PAW to prevent nitrogen loss. Ar + 1-3% N_2 as shielding and 90% N_2 + 10% H_2 as backing gas are consequently preferred over pure argon. Normally, a filler of type 22 9 3 NL should be used for optimum properties in the as welded condition.

Products

- Plate, sheet and coil
- Welded pipe and tube
- Fittings

Product specifications and approvals

The steel is not yet included in any national standard. Work is in progress for both ASTM and EN standardization of flat and tubular products. Patent pending.

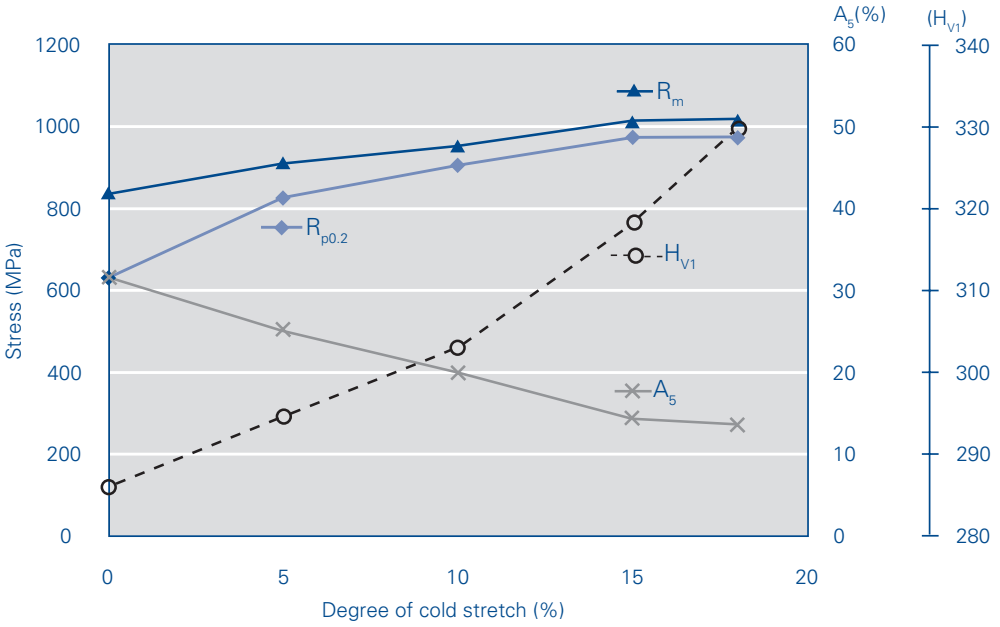

Fig. 4. Mechanical properties of 1 mm LDX 2404™ after cold working.

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Outokumpu is a global leader in stainless steel. Our vision is to be the undisputed number one in stainless, with success based on operational excellence. Customers in a wide range of industries use our stainless steel and services worldwide. Being fully recyclable, maintenance-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]

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