

## STEEL GRADES

AvestaPolarit	EN	ASTM
SAF 2304 <sup>®</sup>	1.4362	S32304
2205	1.4462	S32205 S31803
SAF 2507 <sup>®</sup>	1.4410	S32750

## CHARACTERISTIC PROPERTIES

- High strength
- High resistance to pitting and crevice corrosion
- High resistance to stress corrosion cracking and corrosion fatigue
- High 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
- Tanks
- Rotors, impellers and shafts
- 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

Duplex stainless steels, also referred to as ferritic-austenitic 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 pitting and uniform corrosion. The duplex micro-structure contributes to their high strength and high resistance to stress corrosion cracking. Duplex steels also have good weldability.

## 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.

**Table 1. Chemical composition**

AvestaPolarit steel name	International steel No		Typical composition, %					National steel designations, superseded by EN			
	EN	ASTM	C	N	Cr	Ni	Mo	BS	DIN	NF	SS
4301	1.4301	304	0.04	0.05	18.1	8.3		304S31	1.4301	Z7 CN 18-09	2333
4404	1.4404	316L	0.02	0.04	17.2	10.2	2.1	316S11	1.4404	Z3 CND 17-11-02	2348
4436	1.4436	316	0.02	0.05	16.9	10.7	2.6	316S33	1.4436	Z7 CND 18-12-03	2343
904L	1.4539	N08904	0.01	0.06	20	25	4.5	904S13	1.4539	Z2 NCDU 25-20	2562
254 SMO <sup>®</sup>	1.4547	S31254	0.01	0.2	20	18	6.1	–	–	–	2378
3RE60	1.4417	S31500	0.02	–	18.5	5	2.7	–	1.4417	–	2376
4460	1.4460	329	0.02	0.09	25.2	5.6	1.4	–	1.4460	Z5 CND 27-05 Az	2324
<b>SAF 2304<sup>®</sup></b>	<b>1.4362</b>	<b>S32304</b>	<b>0.02</b>	<b>0.10</b>	<b>23</b>	<b>4.8</b>	<b>0.3</b>	–	<b>1.4362</b>	<b>Z3 CN 23-04 Az</b>	<b>2327</b>
<b>2205</b>	<b>1.4462</b>	<b>S32205*</b>	<b>0.02</b>	<b>0.17</b>	<b>22</b>	<b>5.7</b>	<b>3.1</b>	<b>318S13</b>	<b>1.4462</b>	<b>Z3 CND 22-05 Az</b>	<b>2377</b>
<b>SAF 2507<sup>®</sup></b>	<b>1.4410</b>	<b>S32750</b>	<b>0.02</b>	<b>0.27</b>	<b>25</b>	<b>7</b>	<b>4</b>	–	–	<b>Z3 CND 25-06 Az</b>	<b>2328</b>

\* Exists also as S31803.

SAF 2304<sup>®</sup>, and SAF 2507<sup>®</sup> are made on licence from AB Sandvik Steel.

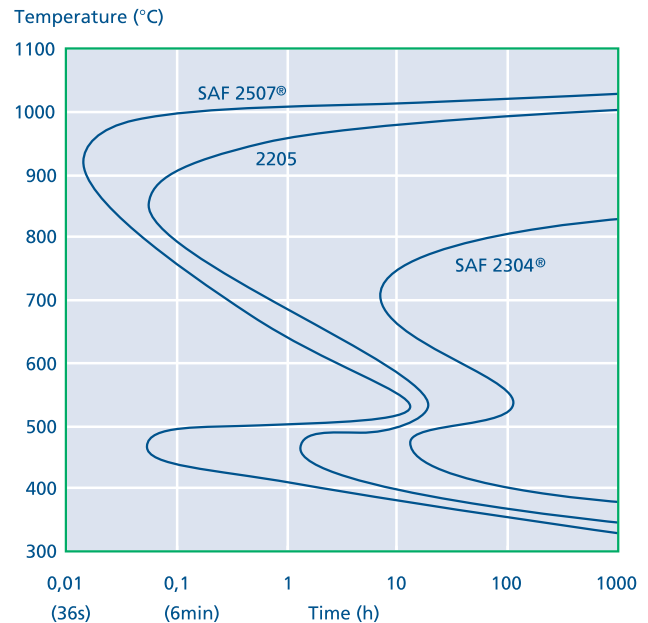
### MICROSTRUCTURE

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 an extremely 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 2-6 show the mechanical properties of the duplex steels. Data according to EN 10088 when applicable. Permitted design values can vary

between different product forms. See the relevant norm for correct values.

**Table 2. Minimum values at 20°C**

			SAF 2304®			2205			SAF 2507®		
			P	H	C	P	H	C	P	H	C
Proof strength	R <sub>p0.2</sub>	MPa	400	400	420	460	460	480	530	530	550
Tensile strength	R <sub>m</sub>	MPa	630	600	600	640	660	660	730	750	750
Elongation	A <sub>5</sub>	%	25	20	20	25	25	20	20	15	15

P = Hot rolled plate. H = Hot rolled strip. C = Cold rolled strip

**Table 3. Typical values at 20°C**

			SAF 2304®			2205			SAF 2507®		
			P	H	C	P	H	C	P	H	C
Proof strength	R <sub>p0.2</sub>	MPa	430	480	545	510	565	605	665	590	665
Tensile strength	R <sub>m</sub>	MPa	660	685	735	750	790	835	800	830	895
Elongation	A <sub>5</sub>	%	35	35	35	35	35	35	35	35	33
Hardness	HB		210	220	225	250	250	250	250	250	255

P = hot rolled plate. H = hot rolled strip. C = cold rolled strip

**Table 4. Impact toughness. Minimum value<sup>1)</sup> for sheet/plate up to 30 mm, Charpy-V, J**

	SAF 2304®	2205	SAF 2507®
20°C	100	100	100
-20°C	100	100	100
-40°C	80	80	80

<sup>1)</sup> Mean value of 3 full-size test bars

**Table 5. Tensile properties at elevated temperatures. Minimum values, MPa**

	SAF 2304®		2205		SAF 2507®	
	R <sub>p0.2</sub>	R <sub>m</sub>	R <sub>p0.2</sub>	R <sub>m</sub>	R <sub>p0.2</sub>	R <sub>m</sub>
100°C	330	540	360	590	450	680
150°C	300	520	335	570	420	660
200°C	280	500	315	550	400	640
250°C	265	490	300	540	380	630

**Fatigue**

The high tensile strength of duplex steels also implies high fatigue strength. Table 6 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, 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 stress of the material.

**Table 6.**

	SAF 2304®	2205	SAF 2507®	1.4404
R <sub>p0.2</sub> MPa	446	540	565	280
R <sub>m</sub> MPa	689	767	802	578
Fatigue strength, MPa	450	510	550	360

Standard deviation of fatigue strength ~ 30 MPa

### PHYSICAL PROPERTIES

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

Table 7. Typical values

		20°C	100°C	200°C	300°C
Density	kg/dm <sup>3</sup>	7,8			
Modulus of elasticity	GPa	200	194	186	180
Linear expansion at (RT → T)°C	X10 <sup>-6</sup> /°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 the AvestaPolarit 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. SAF 2304<sup>®</sup> is in most cases equivalent to 1.4436, and the other more highly-alloyed duplex steels show even better resistance, see Figure 2, an isocorrosion diagram in dilute sulphuric acid. In sulphuric acid contaminated by chloride ions, 2205 shows much better resistance than 1.4436 and a similar resistance to that of 904L, as shown in 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<sup>®</sup> and to some extent also 2205 can be used in dilute hydrochloric acid, see 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,

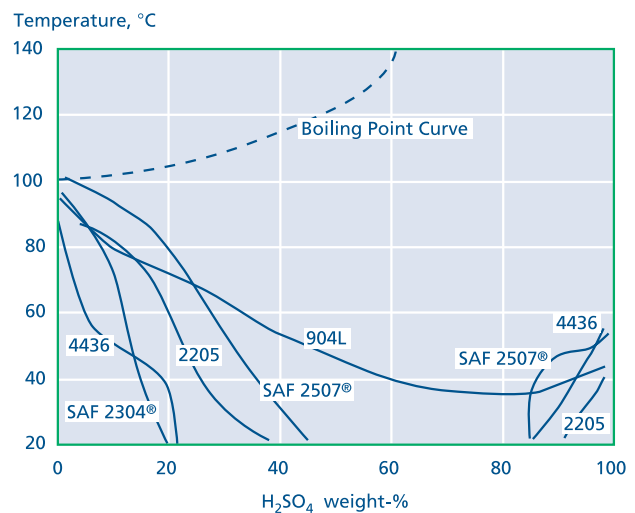


Fig. 2. Isocorrosion curves, 0.1 mm/year, in sulphuric acid.

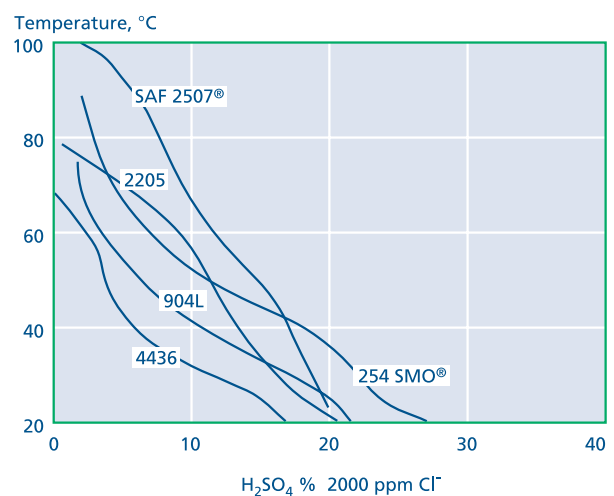


Fig. 3. Isocorrosion curves, 0,1 mm/year, in sulphuric acid containing 2000 ppm chloride ions.

e.g. in the form of chlorides and fluorides. 2205 offers very good resistance even in acids that have a fairly high halide content. See Figure 5.

In very strongly oxidising acids, e.g. nitric acid, non-molybdenum alloyed steels are often more resistant than the molybdenum-alloyed steels. SAF 2304<sup>®</sup> is a good alternative here, because of its high chromium content in combination with low molybdenum content.

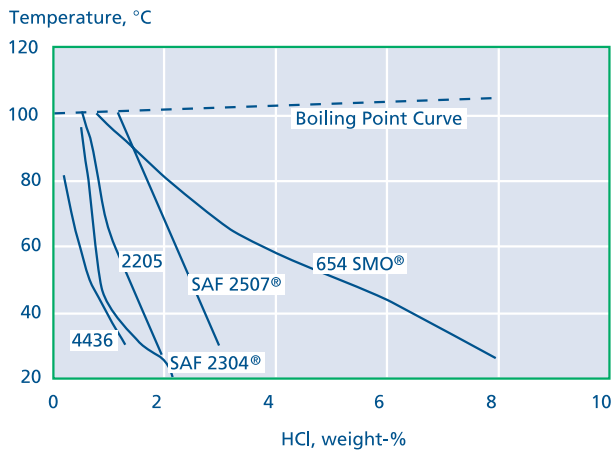
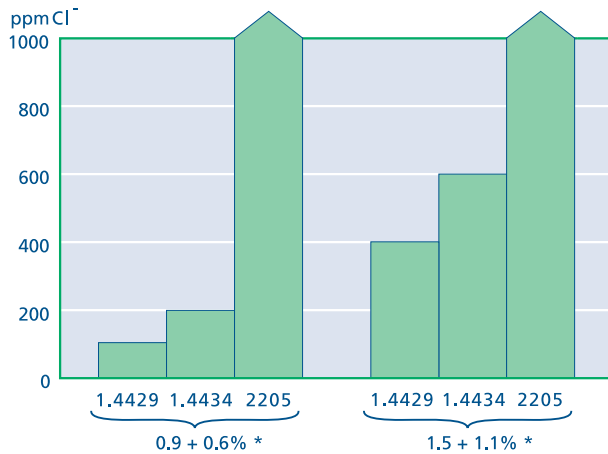


Fig. 4. Isocorrosion curves 0.1mm/year, in hydrochloric acid.



\* Inhibitors: iron- +aluminium-oxides

Fig. 5. Uniform corrosion in wet process phosphoric acid. Maximum acceptable chloride contents at various inhibitor levels. The diagram shows limit values for three AvestaPolarit 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 three duplex steels show considerable differences in this respect. SAF 2304<sup>®</sup> is on a level

with conventional molybdenum-alloyed steels of the 1.4401 type, while 2205 is on a level with 904L and SAF 2507<sup>®</sup> 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 AvestaPolarit, 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 is shown in Figure 6.

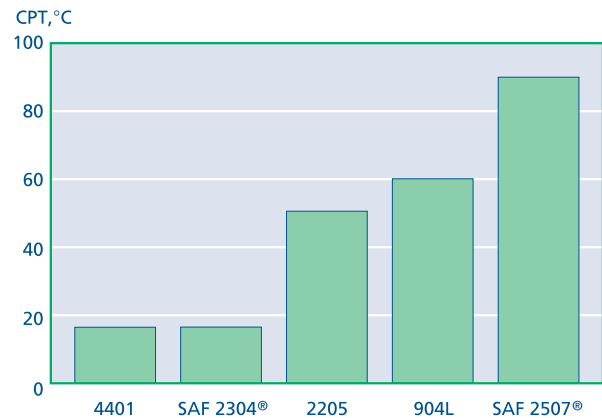


Fig. 6. Critical pitting corrosion temperatures (CPT) in 1M NaCl measured with the Avesta Cell. Typical values.

When ranking the resistance to crevice corrosion it is common to measure a critical temperature at which corrosion occurs in a well-defined solution. The critical crevice corrosion temperature (CCT) measured in 6% FeCl<sub>3</sub> in conformance to a modified variant of ASTM G48 (MTI-2) is presented in Figure 7.

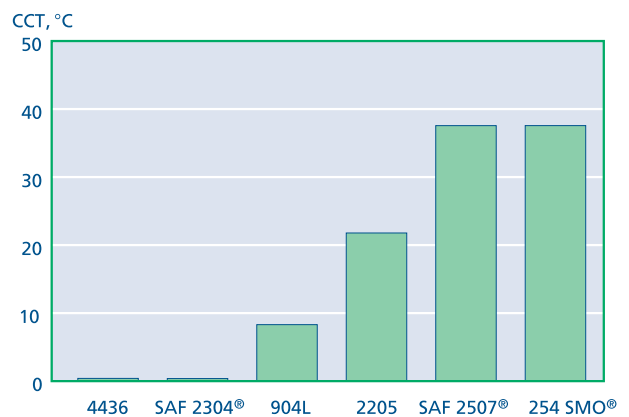
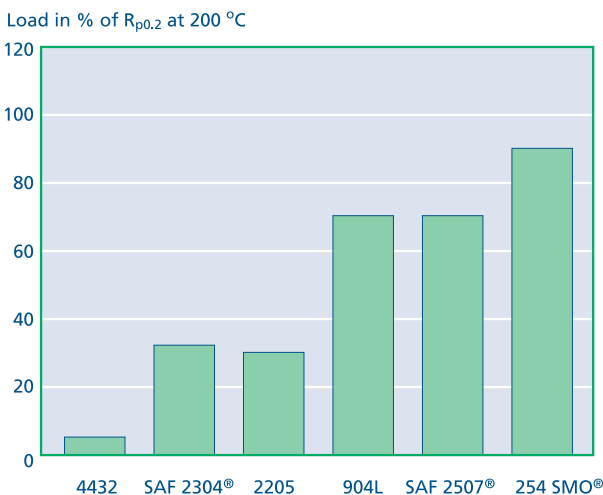


Fig. 7. Critical crevice corrosion temperature (CCT) in 6% FeCl<sub>3</sub> according to MTI Manual No. 3 Method MTI-2.

### 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, due to a continuous ferritic phase, are much less sensitive to this type of corrosion.

Different methods are used to rank the different grades of steel 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. In this manner the threshold value is determined for the stress leading to 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 1.4436 type.



**Fig. 8.** Threshold values for the relative stress leading to rupture after up to 500 h under strong evaporative conditions.

### Sulphide stress corrosion cracking

In the presence of hydrogen sulphide and chloride solutions 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.

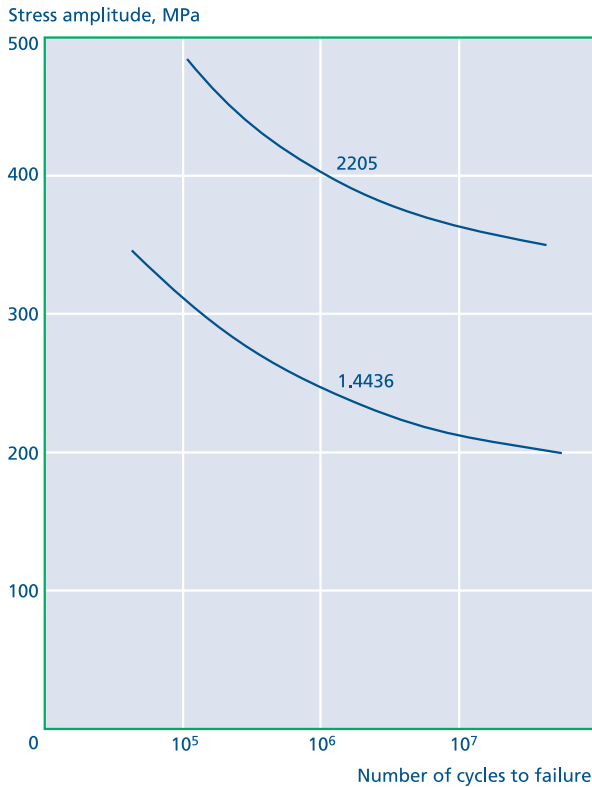
2205 and SAF 2507® are both included in NACE's list of approved materials in hydrogen sulphide environments – MR0175 (“Sulphide Stress Cracking Resistant Metallic Materials for Oilfield Equipment”).

According to NACE MR0175, wrought 2205 in the solution-annealed condition is acceptable in sour service if its hardness does not exceed 28 HRC. Solution annealed and cold worked 2205 may be used at all temperatures up to 232°C (450°F) in sour environments, if the partial pressure for hydrogen sulphide does not exceed 0.002MPa (0.3psia), i.e., provided the yield strength of the material is not greater than 1100 MPa (160 ksi) and provided its hardness is not greater than 36 HRC.

Solution annealed SAF 2507® may be used to a maximum of 32HRC in sour environments up to a temperature of 232°C (450°F) if the hydrogen sulphide partial pressure does not exceed 0.01MPa (1.5psia).

**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 1.4436 in synthetic seawater are shown in Figure 9. The corrosion fatigue strength of 2205 is considerably higher than that of the other tested steel.



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

**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.

**FABRICATION**

**Hot forming**

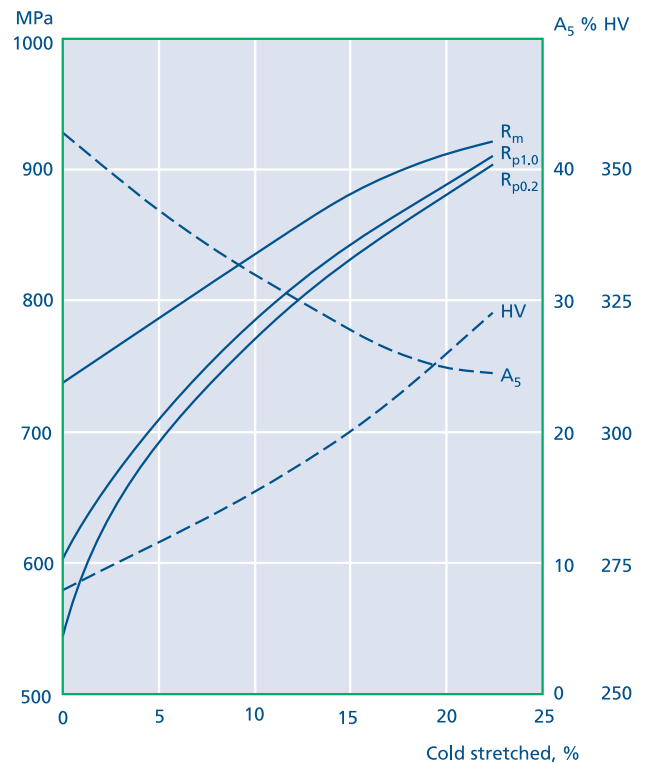
Hot working is performed at the temperatures illustrated in Table 8. It should, however, be observed that the strength of the duplex materials is low at high temperatures. Quench annealing should normally be carried out following hot working.

**Table 8.** Characteristic temperatures, °C

	SAF 2304®	2205	SAF 2507®
Hot forming	1100 - 900	1150 - 950	1200 - 1025
Quench annealing	950 - 1050	1020 - 1100	1040 - 1120
Stress relief annealing	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 duplex steel. Figures 10 and 11 show diagrams of the work hardening of SAF 2304® and 2205 respectively.



**Fig. 10.** 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. One must be prepared for a relatively high spring back because of the high yield point.

Quench annealing is normally recommended after more than 10% cold deformation.

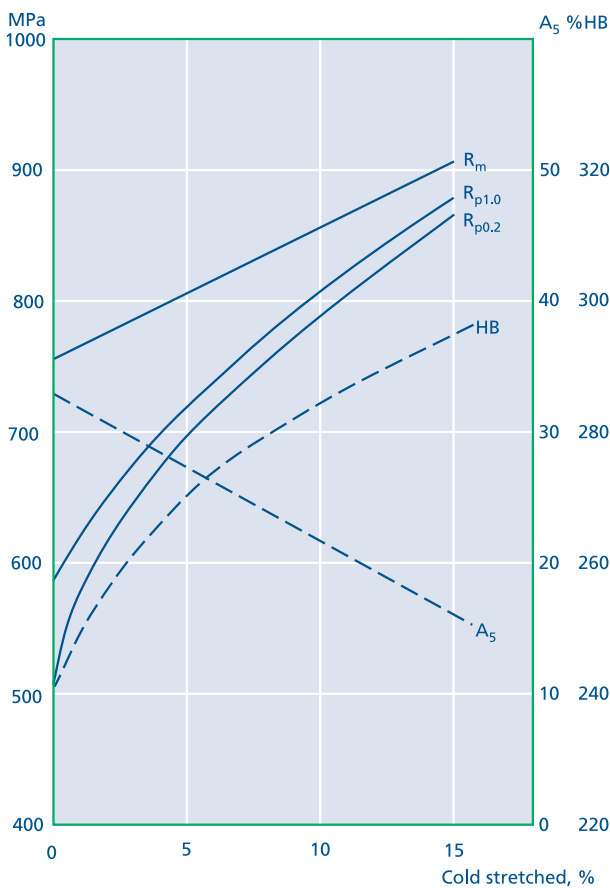


Fig. 11. Mechanical properties of 2205 after cold working.

### 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 550-600°C. Further information concerning these operations is available from AvestaPolarit.

### Machining

Duplex steels are generally more difficult to machine than conventional austenitic stainless steel such as 1.4436, and have different machining properties than those of high-alloyed austenitic steels. The main difference is that duplex steels are relatively easier to machine with high-speed steel tools than with cemented carbide tools compared to austenitic stainless steels with similar alloy content.

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 1.4436. Note, however, that the machinability index does not describe the relative difficulty between high-speed steel and carbide tools. Further information is provided in "Machining Guidelines" that are available for all SAF 2304®, 2205 and SAF 2507® steels.

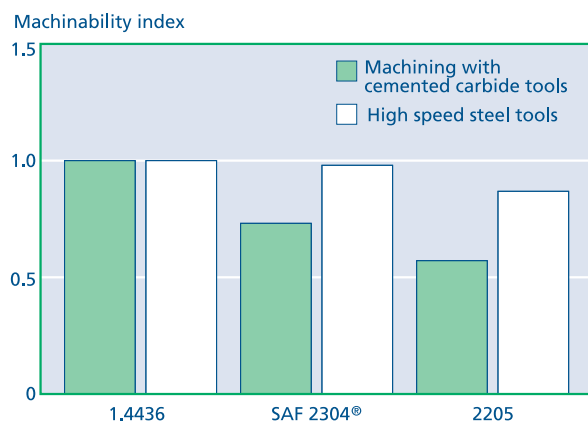


Fig. 12. Machinability index for duplex and some other stainless steels.

## Welding

Duplex steels generally have good weldability and can be welded using most of the welding methods used for 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 in a properly made weld 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 AvestaPolarit 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.

- 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.

AvestaPolarit 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 9). These filler metals ensure weld properties comparable to those of the parent metal.

For more detailed information concerning the welding of duplex steels, please refer to AvestaPolarit Welding's special leaflets "How to weld AvestaPolarit 2205", which is applicable for both 2205 and SAF 2304®, and also in "How to weld AvestaPolarit SAF 2507®".

**Table 9. Welding consumables**

Product form	Designation		Typical composition, %					Ferrite, FN WRC-92
	AvestaPolarit	AWS	C	Cr	Ni	Mo	N	
For welding SAF 2304®								
Electrode	2304 AC/DC	–	0.02	24.5	9.0	–	0.12	30
For welding 2205 and SAF 2304®								
Electrode	2205 AC/DC	E2209-17	0.02	23.0	9.5	3.0	0.15	30
	2205 PW	E2209-17	0.02	23.0	9.5	3.0	0.17	30
	2205 Basic	E2209-15	0.02	23.0	9.5	3.0	0.16	30
Wire	2205	ER2209	0.02	23.0	8.5	3.1	0.17	50
Flux cored wire	2205	E2209T0-4	0.03	23.0	9.0	3.1	0.13	50
	2205-H	E2209T0-4	0.03	23.5	9.5	3.4	0.14	50
	2205-PW	E2209-T1-4	0.03	23.0	9.5	3.5	0.16	45
For welding SAF 2507®								
Electrode	2507/P100	–	0.03	25.5	10.0	3.6	0.23	30
Wire	2507/P100	–	0.02	25.0	9.5	4.0	0.25	50

### PRODUCTS

*Table 10.*

Hot rolled plate, sheet and strip	Dimensions according to AvestaPolarit product program.
Cold rolled sheet and strip	Dimensions according to AvestaPolarit product program.
Bars and forging	Supplied by AvestaPolarit Valbruna AB, Karlstad.
Tube and Pipe	Welded tubes and pipes are supplied by Avesta Sandvik Tube AB. <a href="http://www.asttube.com">www.asttube.com</a>
Pipe fittings	Threaded pipe fittings and flanges are manufactured by Calamo Nords AB, Molkom. Welded pipe fittings are supplied by AvestaPolarit ABE AB, Örnsköldsvik, and Calamo Nords AB, Molkom.
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 AvestaPolarit Welding AB, Avesta. Welding consumables are manufactured to conform to the requirements of the nuclear power industry.

## 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
prEN 10217-7	Welded steel tubes for pressure purposes – Stainless steels
EN 10272	Stainless steel bars for pressure purposes
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
VdTÜV WB 496	Ferritisch-austenitischer Walz- und Schmiedestahl
NACE MR0175	Sulphide stress cracking resistant material for oil field equipment
Norsok M-CR 630, MDS D45	

AvestaPolarit 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.

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**AvestaPolarit AB**  
R&D Centre Avesta  
SE-774 80 Avesta, Sweden  
Tel: +46 (0)226 810 00  
Fax: +46 (0)226 813 05

[www.avestapolarit.com](http://www.avestapolarit.com)

