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Dear Reader,

There is in Swedish a rather stupid saying, which translated into English becomes something like "Anybody waiting for something good can never wait too long". It may have had some bearing in the past when time was in surplus but it surely doesn´t have in a modern society. The keywords today are "just in time", "time shearing" and similar and waiting for something is just frustrating.

Anyhow, we apologise for the time it has taken, we appreciate that you have had patience, but finally **acom** *is back on track again. The aim will be four issues annually but due to the timing this year you will get two, but each will contain two articles instead.*

Enjoy the reading!

Jan Olsson

TECHNICAL EDITOR

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Fatigue behaviour of stainless steel welds

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Keywords: Stainless steel, Duplex, Fatigue strength, Fatigue design, Welds

Stainless steels are used more and more as a structural material due to their good mechanical properties combined with high corrosion resistance. One of the most frequent causes of failure in constructions, besides corrosion, is fatigue or corrosion fatigue. However, there are fewer data available on fatigue properties for stainless steels than for ordinary structural steels, which, to some extent could limit their use.

A standard austenitic stainless steel (316L) was compared with two types of duplex steels (2205 and SAF 2304) using different welding methods and different material thicknesses. High cycle fatigue tests across the welds were performed both with polished specimens and also with specimens having the weld reinforcement intact. The results confirmed that the duplex steels have higher fatigue strength than austenitic stainless steels. The superior behaviour of the duplex parent material was to a great extent maintained also in the weldments. Submerged arc welds (SAW) showed even higher fatigue strengths than the base material. However, the duplex welds produced with gas metal arc welding (GMAW) showed a slight reduction of the fatigue strength compared to the parent material. Corrosion fatigue tests in synthetic seawater environment (3% NaCl) at a frequency of 1 Hz resulted in 25% reduction of the fatigue strength of 316L compared to 10% reduction for the duplex grade 2205.

Results for butt welds (GTAW and GMAW) in 2205 show that the stress concentration at the weld toe greatly influences the fatigue performance. The favourable geometry of the GTA weld profile gives exceptionally high fatigue strength. However, when stress raisers become more severe, e.g. load-carrying fillet welds, the fatigue strength drops significantly and becomes independent of the material's static strength.

Nevertheless, stainless steels and especially duplex stainless steels show very promising fatigue behaviour on the same level or better than ordinary structural steel.

Background

Traditionally, stainless steels have been used mainly for corrosion protection purposes in various environments. For that reason the focus has been to choose the optimal alloy from corrosion point of view. Corrosion data are now readily available for a great number of steel grades and corrosion environments. Also the effect of welding has been thoroughly investigated and is reported in the literature.

One of the most frequent causes of failure in materials, including stainless steels, is (corrosion) fatigue. The failures often occur at stress raisers in or near welds. Conventional stainless steels have comparatively low strength levels and notch sensitivity. For higher strength grades such as duplex stainless steels higher notch sensitivity is expected needing more concern in design, particularly if the strength shall be fully utilised.

For several reasons there is an increased use of stainless steel as a construction material in less severe environments. The current design rules for dynamic loading of steels are based on data for C-Mn steels. It has been shown that fatigue properties of stainless steels compare favourably with C-Mn steels resulting in a conservative design when using stainless steels. The objective with this paper is to shed some further light on the fatigue behaviour of stainless steels with special focus on welds and on duplex stainless steels. This paper will be limited to high cycle fatigue as such data are more relevant for materials design purposes than low cycle fatigue.

Introduction

FATIGUE PROPERTIES OF WELDS

Stainless steels have been subjected to extensive fatigue documentation during many decades and there are plenty of data available [1–3]. As is the case with C-Mn steels the fatigue strength for both austenitic and duplex stainless steels is related to the yield and tensile strength levels. The general rules valid for other materials can also be used for stainless steels. Thus a higher strength material with higher fatigue strength will also have increased notch sensitivity. A smooth surface and freedom from defects (such as non-metallic inclusions) also have positive effect on the fatigue life of stainless steels.

Many investigations have shown that duplex steels, with a higher strength level than austenitic steels, have superior fatigue strength [4–6]. In many cases the fatigue strength of duplex steels is on level with the static yield strength. The effect of the duplex microstructure is to maintain the fineness of the structure, giving a high strength. Several works have studied the initiation stage mainly in strain controlled fatigue tests. The initiation can occur in either or in both phases depending on the conditions [7–8]. A concept of microstructural barriers for short crack propagation can be used to explain the role of the individual phases in duplex steel [9]. The general conclusion is thus that the presence of two phases seems to have a retarding effect on the initiation of fatigue cracks.

Concerning the fatigue behaviour of stainless welds there is less published information available. In cases where welds actually have been tested there is little or no information on the welding process and welding parameters. Such variables could have a large impact on properties including the fatigue behaviour.

For conventional austenitic stainless steels the weld metal generally has a slightly higher strength than the base material partly because of a small content of ferrite. Duplex steels show a similar relationship when welded with the recommended filler materials with enhanced Ni content. However, other welding procedures can result in widely variable ferrite contents and strengths. Depending on the welding method the oxygen level and thereby the inclusion content in the weld metal will vary considerably. For a high alloy austenitic stainless steel welded with Ni-base filler, gas tungsten arc welds (GTAW) showed markedly higher fatigue strength than submerged arc welds (SAW) [10]. This result was attributed to a lower inclusion level in the former welds but possibly also presence of microfissures in the SAW. Different welding parameters can also give rise to varying residual stresses and strain in the weld area, which should have large effects on the fatigue results.
Normally, fatigue testing of welds is done with specimens removed transverse to the weld seam. This approach can be used to assess the fatigue properties of the weld metal as such if the specimen is machined to a smooth reduced section. The limited information given for such con-figurations indicates that high quality welds show fatigue properties comparable with those of the parent metal.

FATIGUE DESIGN OF WELDED STRUCTURES

The design part will cover fatigue performance of stainless steel joints in as welded condition in comparison with smooth specimen data for parent and welded materials. Design data on fatigue of welded structural steels has gradually been built up and recommendations have been established by The International Institute of Welding (IIW) [11], Eurocode 3 [12], etc. Different types of standardised structures have been tested to cover different types of load cases such as butt welds, fillet welds etc. Depending on the structure's susceptibility to fatigue failure, each structure has been given a fatigue class i.e. FAT class in the IIW designation system. The FAT class gives the allowable stress range at 2.106 cycles. This method is often refereed as the nominal stress approach.

Stainless steel is increasingly used for structural purposes with the consequence that engineers are looking for fatigue design data of stainless steel in the same way as they do when using structural steel. However, the design guidelines available, e.g. Eurocode or IIW, are built upon data of C-Mn steels only. To make it simple, a first assumption is to use the guidelines for C-Mn steels when using stainless steels.
The outcome of this approach is probably satisfactory in most cases, because the fatigue behaviour of welded joints is dominated by the joint geometry and similar crack growth behaviour occurs in C-Mn and stainless steel. However, the intention behind these guidelines is to provide structural integrity for the used material and the levels of the fatigue classes are derived from statistical evaluation of a great number of tested specimens from different laboratories and welding procedures etc. and a certain confidence against fracture has been established. The weakness in using the guidelines for the nominal stress approach is the question of whether or not the real structure can be idealised for comparisons with a standardised geometry e.g. butt weld, fillet weld. Loading direction, welding procedures, residual stresses etc. have to be considered as well. Nevertheless, supplementary methods to the nominal stress approach have come into use to improve the fatigue design process by the use of finite element analysis (FEA), the hot spot stress and the fracture mechanics approach. All these methods for fatigue design have their advantages and disadvantages. However, to get reliability in all these methods it is essential to have knowledge of the behaviour of the specific material. Stainless steel differs significantly from C-Mn steel on a metallurgical scale, which in turn affects the mechanical properties. Therefore, they should be tested in the same way as C-Mn steels to make it possible to establish fatigue design recommendations, which provides structural integrity. Furthermore, stainless steel cannot be looked upon as one single material group. It is essential to divide stainless steel into at least three groups that differ significantly; ferritic steels, austenitic steels and ferritic-austenitic (duplex) stainless steels.

Unfortunately, the limited number of fatigue data available on welded stainless steel has led to preconceived misunderstanding of the fatigue behaviour of stainless steels compared to C-Mn steels. Individual sets of results should be treated with caution. Variations in the quality of the parent material, and in testing procedures as well as welding procedures influence the results and will create scatter in the data. The weakest spot along the weld, even if it were just a single imperfection, would most likely initiate the crucial crack. Therefore, fatigue testing at different laboratories with different materials and welding techniques etc. is required before it is meaningful to established fatigue design guidelines for stainless steels. IIW has no recommendations for stainless steel at present time. Eurocode 3 has included stainless steels in the last draft. Stainless steels are regarded as equivalent to C-Mn steels.

There are not many studies carried out on fatigue performance of welded stainless steels and especially not for duplex stainless steels [13–17]. Some recent data will be presented in this paper, however it is not a complete coverage of the published data in the literature until today. It will anyway give indications on the fatigue levels for welded stainless steels.

Materials

One austenitic (316L or EN 1.4404) and two duplex (UNS S32304 or EN 1.4362 and UNS S32205 or 1.4462) stainless steels were tested. SAF 2304 is a trademark of Sandvik Steel. For simplicity the duplex grades are listed as 2304 and 2205 in this paper. The compositions are given in Table 1. The 316L material in 20 mm thickness had slightly higher Mo and Ni contents than the thinner 3 mm material. Commercially produced plate and sheet material

Alloy, thickness	C	Si	Mn	P	S	Cr	Ni	Mb	N
316L, 20 mm	0.021	0.6	0.8	0.028	0.001	17.7	12.6	2.6	0.04
316L, 3 mm	0.021	0.5	1.1	0.031	0.001	17.6	11.2	2.1	0.06
2205, 20 mm	0.020	0.4	1.6	0.020	0.001	22.1	5,8	3.0	0.18
2205, 3 mm	0.017	0.4	1.6	0.022	0.001	22.2	5.8	3.0	0.16
2304, 20 mm	0.021	0.4	1.5	0.021	0.001	22.9	4.7	0.2	0.10
2304, 3 mm	0.015	0.5	1.6	0.020	0.001	22.8	4.9	0.3	0.09

Table 1: *Chemical composition of tested alloys*

in 20 and 3 mm thickness, respectively, were used. Tensile properties transverse to rolling direction are listed in Table 2. The duplex steels base materials contained 47 and 43 % ferrite, respectively.

In order to investigate the influence of weld type (with varying cleanliness) different welding methods were used (Figure 1). Gas metal arc welding (GMAW) and SAW were used for 20 mm materials and GMAW and GTAW for 3 mm materials. For the fillet welds, flux cored arc welding (FCAW) was used as well. The welds were orientated in the rolling direction. Type ER 316LSi-filler was used for the 316L material, and Type ER 2209-filler for both duplex grades. The welding parameters are shown in Tables 3a and 3b. Tensile testing was performed both longitudinally (i.e. the weld metal) and transverse to the rolling direction of the welded hot rolled material. The results were used to relate to the fatigue data and are not displayed in this report. Welds and base materials were thoroughly characterised concerning chemical composition, microstructure and hardness, but all data will not be reported in this paper.

Alloy, thickness	$R_{p0,2}$ MPa	$R_{p1.0}$ MPa	R_m MPa	A_5 %	HV5
316L, 20 mm	280	323	578	54	143
316L, 3 mm	279	309	582	57	146
2205, 20 mm	507	582	759	38	227
2205, 3 mm	607	700	835	35	250
2304, 20 mm	450	508	672	37	208
2304, 3 mm	537	604	729	31	230

Table 2: *Mechanical properties of tested parent materials, transverse direction*

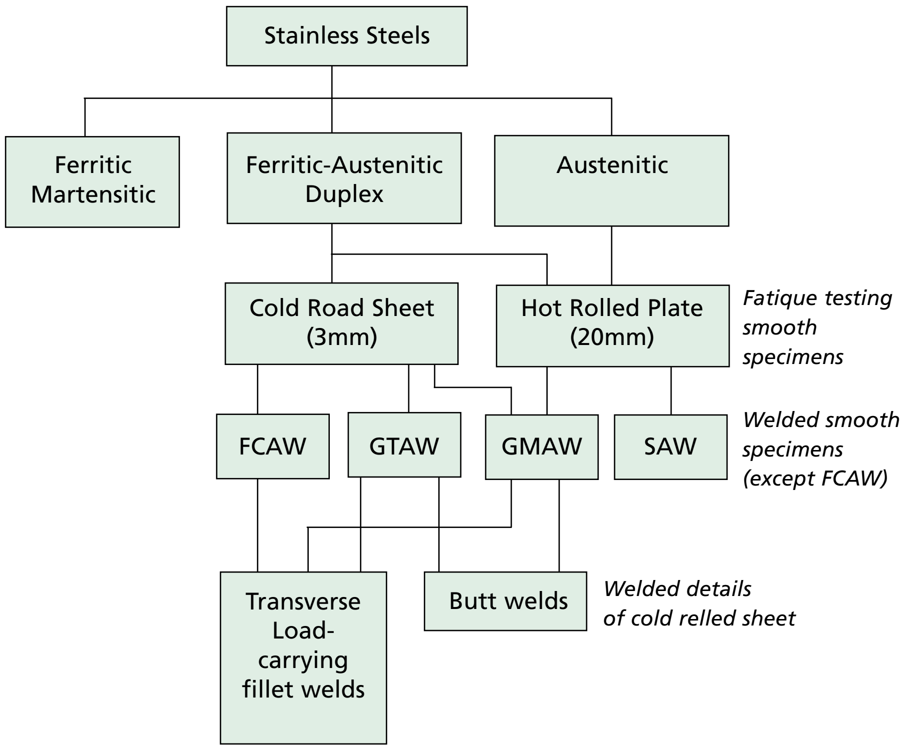

Figure 1. *Test matrix showing the welded stainless steels used in this study*

	Steel/Weld	Joint type	Shield/root gas	No of weld passes	Arc energy (kJ/mm)	Filler	WM Ferrite content
	316L/GTAW	X	Ar/Ar	2	0,9–1,3	316LSi	–
	316L/GMAW	I	Ar+2%O_2/Ar	1	0,5	316LSi	–
	2205/GTAW	X	Ar/Ar	2	0,9–1,2	2209	72
	2205/GMAW	I		1	0,5	2209	56
	2304/GTAW	X	Ar/Ar	2	0,9–1,0	2209	81
	2304/GMAW	I	Ar-He-O/Ar	1	0,5	2209	61
	316L/GMAW	U	Ar+NO/-	10	1,2–1,5	316LSi	6
	316L/SAW	U	Flux	9	1,8	316LSi	9
	2205/GMAW	U	Ar-He-O/-	12	1,7	2209	45
	2205/SAW	U	Flux	9	1,8	2209	47
	2304/GMAW	U	Ar-He-O/	11	1,7	2209	48
	2304/SAW	U	Flux	8	1,8	2209	46

Table 3a: *Welding parameters for smooth butt welds*

t (mm)	Steel /Weld	Joint type	Shield/root gas	No of weld passes	Arc energy (kJ/mm)	Filler	WM Ferrite content
3	2205/GTAW	B	Ar/Ar	2	0,9–1,2	2209	72
3	2205/GMAW	B	Ar-He-O/Ar	1	0,5	2209	56
3	2205/GTAW	F	Ar	–	0,5	2209	60
3	2205/GMAW	F	Ar+2%O_2	–	0,3	2209	59
3	2205/FCAW	F	75%Ar+25% CO_2	–	0,6	2209	59

Table 3b: *Welding parameters for butt (B) and fillet (F) welds*

Experimental

In this study both smooth and as welded specimens according to Figures 1–2 were fatigue tested. Pulsating fatigue testing was carried out in servo hydraulic testing machines in air at a frequency of 20 Hz and the stress ratio R=0.1. The test specimens were taken across the rolling direction. The testing was performed in air, at 20°C. Corrosion fatigue tests were performed at a frequency of 1Hz and a stress ratio of R=0.1 in 3% NaCl solution. The fracture surface of the test specimens which failed before $2{\cdot}10^6$ cycles, at their respective stress levels, were studied in Scanning Electron Microscope (SEM).

For the smooth specimens fatigue results were evaluated using the staircase method (about 30 specimens). The fatigue strength (RD), standard deviation (s), and RD/Rm were calculated. The as welded specimens were evaluated using SN-curves.

Results and discussion

WELD PROPERTIES

Fatigue test results

Parent material: The ratio between measured fatigue and tensile strength for all 20 mm parent materials was roughly 2/3 (RD/Rm ratio in Tables 4–5. Thus the duplex steels, having a higher strength, show approximately 20–40% higher fatigue strength compared to the austenitic steel. The 3 mm duplex materials have higher tensile strengths also

Grade	R_D MPa	R_{Dmax} MPa	s* MPa	R_m	R_D/R_m
316L	203±165	368	29	578	0,64
316L SAW	218±179	397	13	590	0,67
316L GMAW	199±163	362	–	580	0,62
2205	283±231	514	17	759	0,68
2205 SAW	298±244	542	–	769	0,70
2205 GMAW	283±232	515	–	764	0,67
SAF 2304	248±203	451	–	672	0,67
SAF 2304 SAW	270±221	491	27	673	0,73
SAF 2304GMA W	275±225	500	17	674	0,74

*Std. dev. calculated at maximum fatigue stress, $R_{Dmax.}$ "–" Indicates either invalid step length or too few specimens tested for relevant calculation of std. dev.

***Table 4:** Fatigue test results, HR plate, 20 mm*

Grade	R_D MPa	R_{Dmax} MPa	s* MPa	R_m	R_D/R_m
316L (a)	168 138	306	–	585	0,51
316L (b)	176 145	321	27	595	0,54
316L (L) GTAW	178 145	323	15	–	–
316L (T) GTAW	168 137	305	35	588	0,52
316L GMAW	172 141	313	27	577	0,54
2205	312 255	567	26	835	0,70
2205 (L) GTAW	265 216	481	–	–	–
2205 (T) GTAW	257 211	468	27	814	0,57
2205 GMAW	240 196	436	33	822	0,53
SAF 2304	290 238	528	13	729	0,72
SAF2304(L)GTAW	267 218	485	20	–	–
SAF2304(T)GTAW	245 201	446	34	729	0,61
SAF 2304 GMAW	221 181	402	–		0,54

*Std. dev. calculated at maximum fatigue stress, $R_{Dmax.}$ "–" Indicates either invalid step length or too few specimens tested for relevant calculation of std. dev.

***Table 5:** Fatigue test results, CR sheet, 3mm*

resulting in increased fatigue strength. However, the austenitic material only shows a marginally higher tensile strength at 3 mm thicness, but a clear reduction in fatigue strength compared to the thicker material.

Welded material: All welds had tensile strengths across the weld similar to the parent material. The thicker welded material exhibited equal or higher fatigue strengths compared to the parent material. On the other hand, for the thinner material, the welded duplex

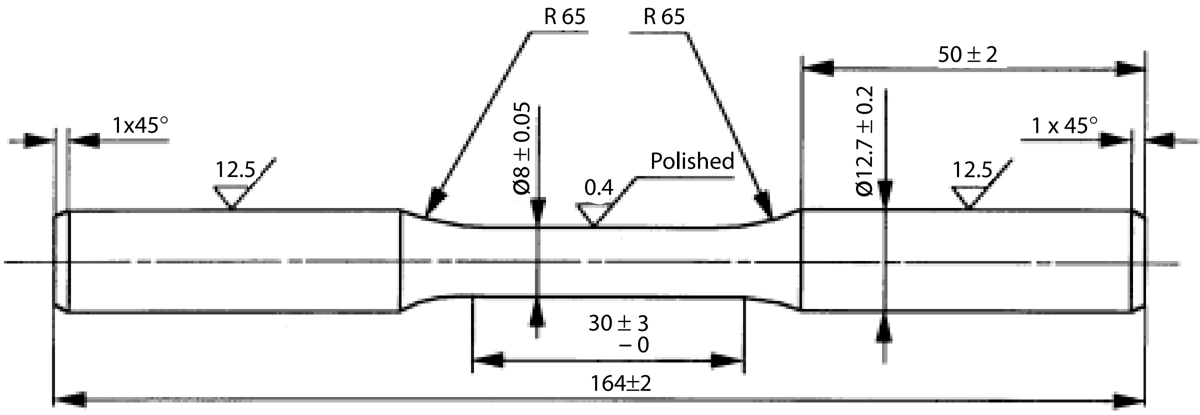

***Figure 2a:** Geometry and dimensions of the smooth fatigue specimen, parent and welded HR plate, 20mm*

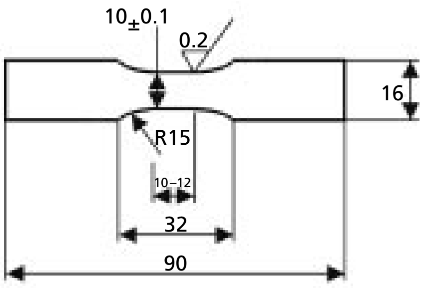

***Figure 2b:** Geometry and dimensions of the smooth fatigue specimen, parent and welded CR sheet, 3mm*

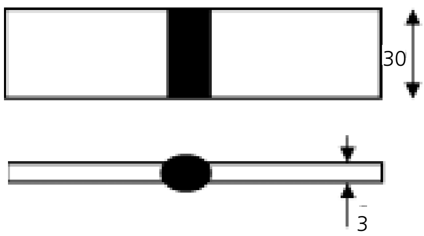

***Figure 2c:** Geometry and dimensions of the butt welded fatigue specimen, GMA and GTA welded CR sheet, 3mm*

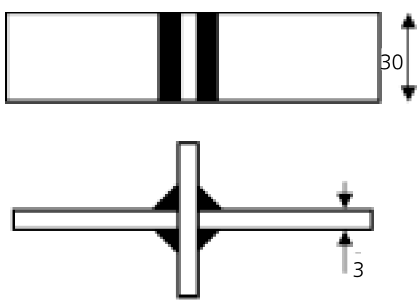

***Figure 2d:** Geometry and dimensions of the load carrying fillet welded fatigue specimen, GMA, GTA and FCA welded CR sheet, 3mm*

Grade	R_D (MPa)	R_{Dmax} MPa	s* MPa	R_{Dcor}/R_{Dair}	R_D/R_m
316L	155±127	282	14	0,766	0,49
316L SAW	190±155	345	–	–	–
2205	250±205	455	–	0,885	0,60
2205 SAW	261±214	475	–	–	–

*Std. dev. calculated at maximum fatigue stress, $R_{Dmax.}$ "–" Indicates either invalid step length or too few specimens tested for relevant calculation of std. dev.

***Table 6:** Corrosion fatigue test results, HR plate, 20mm*

materials showed reduction of fatigue strength compared to the parent material, with GMA welds having the lowest fatigue strengths. The austenitic steel had comparable fatigue strength for welds and for parent material in both gauges with the lowest values for the thinner material.

There is a good correlation between hardness and fatigue strengths for the parent material. However, the fatigue data of welded 20 mm materials show only a weak correlation to hardness measurements. The SAW welds showed the highest hardness values and they have also the highest fatigue strength. The GMA welds (2205 and 316L) have higher hardness compared to parent material but still the lowest fatigue limit values (lower than both parent material and SA welded material). However, no consideration was taken to whether or not the crack propagated through the weld or the parent material, when the fatigue strength was calculated.

Corrosion fatigue test results

The results in Table 6 show that the fatigue strength decreases 10% for the duplex 2205 grade and almost 25% for the austenitic

316L grade in synthetic seawater environment. In the case of 316L indications of corrosion pits on the fracture surfaces wereobserved in connection to surface defects as scratch marks or ferrite bands. Such pitting attacks were not as clearly visible on 2205, which reflects the higher corrosion resistance of 2205. For SA welded materials of 316L and 2205 the fatigue strength is higher than for the parent materials.

Discussion

Fatigue tests on smooth specimens with the weld reinforcement removed and no notches present give information mainly on the influence of metallurgical factors. The fatigue data obtained in this work are in essence in accordance with literature data [3]. Both steel types exhibit fatigue strength levels close to the yield strength. The fatigue strength obtained for 3 mm duplex parent material is higher than for 20 mm material. This result was expected because yield and tensile strengths are higher for the thinner material, which is the result of a finer microstructure. The lamella spacing is approximately 5mm for the 3 mm material, compared to about 25 mm for the 20 mm plate.

For the austenitic steel the thinner gauge material showed lower fatigue strength in spite of a higher tensile strength. Also here the 3 mm material had a finer microstructure; the grain size was 18 mm compared to about 30 mm for the thicker material. One reason for the unexpectedly low fatigue strength could be connected to Al2O3 particles from the specimen preparation detected on the fracture surface at the initiation site. This effect could well be more pronounced for the softer austenitic material.

The welded 20 mm materials showed fatigue strengths close to or above those of the parent materials even though the defect level in these welds seemed comparatively high. No harmful effect of multi-pass welding could thus be observed. The fracture analysis of the fatigue specimens showed that cracks did not run preferentially in the weld metal of SA welds. For GMA welds in 2205, however, most cracks initiated in the weld metal while 2304 showed the opposite behaviour. The fatigue strength for the welded 3 mm materials is lower than those of the parent materials especially for the duplex grades. The defect levels in these welds were not larger than in the thicker material. One reason for the lower fatigue values could be differences in microstructure. Compared to the base material these welds contain clearly higher ferrite levels and have a coarser microstructure. For the duplex steels the GMA weld had slightly lower hardness than the base material. However, this difference did not result in preferential cracking in the welds. For all 3 mm materials the surfaces of the specimens were coarsely polished and most of the fatigue cracks were initiated at scratch marks in the HAZ, which could be more sensitive.

To summarise the results on tests of smooth welded stainless steel specimens, the fatigue life reached the level of the thicker base material irrespective of welding method. The duplex steels have clearly higher fatigue strength than the austenitic steels. The thinner duplex base materials had higher strengths resulting in higher fatigue values. However the welds did not meet these higher values. In fact, the thinner welds had even lower fatigue strengths than the 20 mm welds. This could be due to different test samples with a less optimal surface preparation. In the case of thicker material, round-machined bars were used. For the thinner material, flat bars with fairly sharp edges were tested. Judging from the thicker gauge materials, the present study did not show any substantial difference in performance of the welding methods used. If welded with adequate control they are fully comparable as far as fatigue is concerned.

In the corrosive environment the fatigue strength at $2 \cdot 10^6$ cycles is lowered to a greater extent for the 316L than for the 2205 which is expected because of the better corrosion properties of the 2205. The fatigue strengths for the SAW welded material of 316L and 2205 are higher than for the corresponding parent materials.

Fatigue design

In this paper data of both austenitic and duplex stainless steels are presented. Nevertheless, the focus will be on duplex steels because very few data have been presented in literature and fatigue properties of welded high strength steel is particularly crucial in the design work. Both heavy structures made from hot rolled plate (10–20 mm) and thinner structures from cold rolled sheet (3 mm) will be covered for duplex steels. For austenitic steels only selected results from hot rolled plates (10–20 mm) will be shown. The joints considered (Figure 3) are:

Figure 3a: *Geometry and application of load, fatigue design specimen, butt weld*

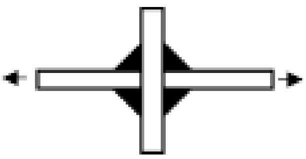

Figure 3b: *Geometry and application of load, fatigue design specimen, transverse load carrying fillet weld*

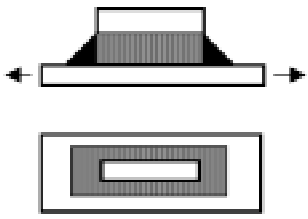

Figure 3c: *Geometry and application of load, fatigue design specimen, longitudinal fillet weld attachment (not used in this investigation, ref. data only)*

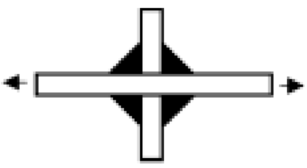

Figure 3d: *Geometry and application of load, fatigue design specimen, transverse non-load carrying fillet weld (not used in this investigation, ref. data only)*

- Transverse butt welds
- Transverse load carrying fillet welds
- Transverse non-load carrying fillet welds ref. data only [13-17]
- Longitudinal fillet welded attachments ref. data only [13-17] The different welding methods used in this compari son were, SAW, GMAW, GTAW and SMAW for the heavy gau ges and GTAW, GMAW and FCAW for the sheets.

Transverse butt-welds

X-ray examination of the GTA and GMA welded specimens (Figure 2c) showed no traces of pores, inclusions etc. in the weld metal and the welds were also checked to confirm full penetration. The results of the fatigue testing are shown in Figure 5, 26 specimens of GTA welds and 16 specimens of GMA welds. Fractography revealed that the majority of he specimens had their crack initiation in the middle of the specimen at the weld toe, confirming that the specimen edges were ground satisfactory to avoid crack initiation at the edges. SEM/EDS-analysis showed no traces of any slag inclusions at the initiation sites.

The fatigue results are surprisingly high for the GTA welded specimens. The stress range was about 0.85 of the smooth welded specimens fatigue strength at (2. 106) cycles (Figure 5). There are of course obvious reasons for that. Firstly, the stress concentration Kt factor is just 1.54 and the

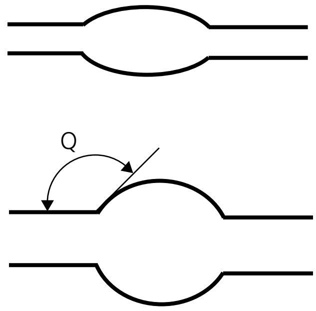

Figure 4a: *Schematic illustrations on cross sections of the GTA (on top) and GMA welded butt joints, Q indicates weld toe angle*

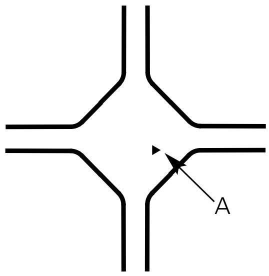

Figure 4b: *Schematic illustrations on cross sections of the GTA welded load carrying fillet joint, A indicates incomplete fusion*

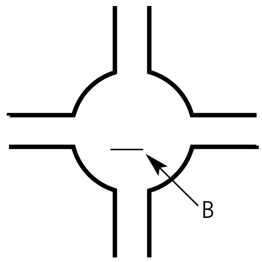

Figure 4c: *Schematic illustrations on cross sections of the GMA welded load carrying fillet joint, B indicates root opening*

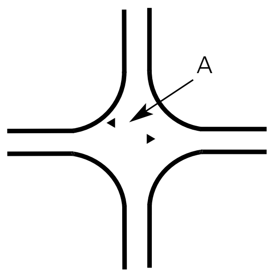

Figure 4d: *Schematic illustrations on cross sections of the FCA welded load carrying fillet joint, A indicates incomplete fusion*

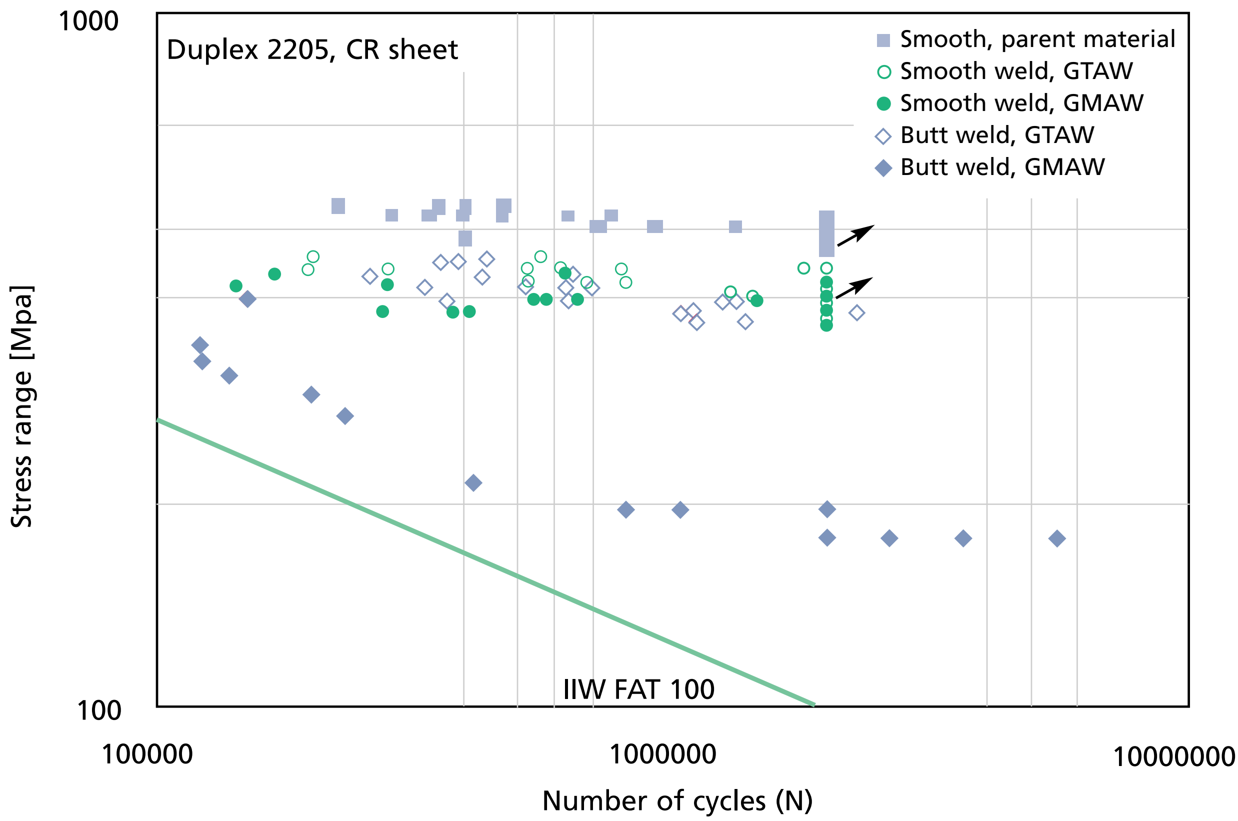

Figure 5: *Fatigue results for parent and welded duplex 2205, CR sheet, 3mm*

weld toe angle about q=160° (Figure 4a), calculated by FEA with the actual weld toe radius obtained from cross section micrographs and imported to the FEA program. Secondly, no pores, slag inclusions or crack-like defects could be found at the initiation sites. It is well known that GTAW gives smooth weld profiles and the method is used for dressing the weld toe to increase the fatigue strength of heavy welded structures. For the GMA welded butt joints there is a significant drop in fatigue strength compared to the GTA welds. The Kt factor is about 2.37 and q=132° (Figure 4a) and even though no imperfections are found at the initiation sites, the weld profile is much more irregular along the weld pass than for the GTA-weld. The higher irregular stress concentration along the weld pass is also shown by the fact that the GMA welded specimens have multiple crack initiation sites. For GTA welded specimens there was usually a single or a double initiation site.

It is interesting to note that if the fatigue notch factor Kf is calculated (not shown in this paper) and compared with the Kt factor, the geometry-induced stress concentration totally controls the fatigue strength reduction compared to smooth specimen for both the GTA and GMA welded butt joints.

If these results are compared with the IIW guideline, butt welds q<30°, the FAT class is 100 and both GMA and GTA welded specimens are well above this level. However, our results are from thin sheets and IIW data are built upon heavy plate thickness around 10 mm. Razmjoo [2] indicated for austenitic and duplex stainless steels fatigue performance comparable to that of C-Mn steels, however, the data are scarce. Results reported for butt-welded joints in austenitic steel [14] are shown in Figure 9. Kosimäki-Niemi [13] have shown that the fatigue strength for butt welds in a duplex stainless steel (similar to 2304) is better than that for an austenitic steel and well above the FAT100 level (Figure 8).

It is also interesting to note that when using GTAW for butt

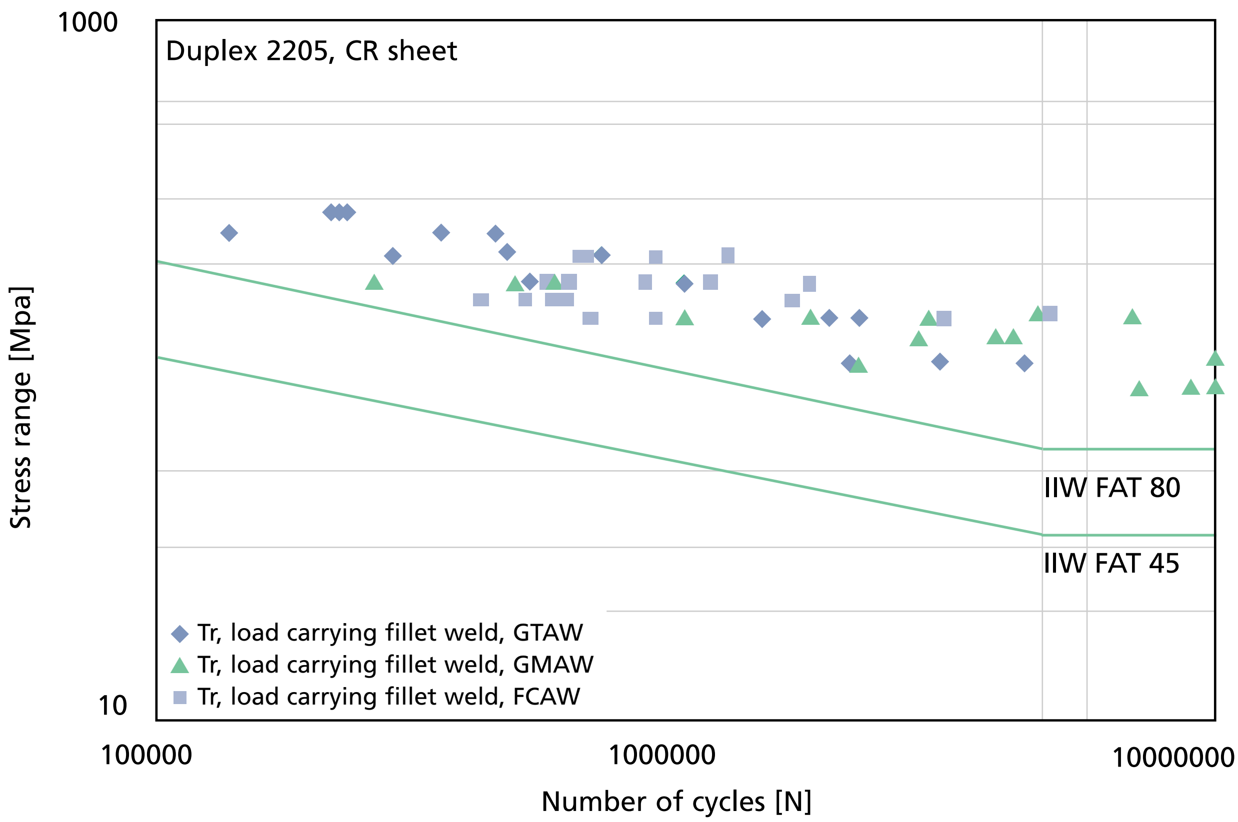

Figure 6: *Fatigue results for load carrying fillet welds in duplex 2205, CR sheet, 3 mm*

joining of duplex stainless steels, these results indicates that the higher static tensile strength in a duplex steel compared to a regular austenitic steel actually contributes to a higher fatigue strength. The common understanding for high strength steel is that the fatigue strength in a welded joint is independent of the static strength. Further testing has to be done to confirm if it is different for duplex stainless steel when the stress concentrations are moderate.

Transverse load carrying fillet welds

The SEM-analyses showed that the GTA, GMA and FCA fillet welded cruciform joints in 3 mm duplex 2205 (Figure 2d) had incomplete fusion and root opening as a result from incorrect welding data. Figures 4b–d illustrate these imperfections. The openings were most pronounced for GTA and FCA welded specimens. Nevertheless, the fatigue results are in general very good for these joints (Figure 6) and they are well above the comparable FAT classes 45–80 (level depending on welding procedure and quality control). The SEM-analyses did not revealed any slag inclusions at the crack initiation sites for any of the welded joints.

The GTA welds cracked from the weld root through the throat at the high stresses and from the weld toe at the low stresses. The toe-initiated specimens had many initiation sites along the fusion line, preferably at the edges of the GTA weld pulses. All the GMA welded joints showed failure from the weld toe. Due to the convex profile of the GMA weld (q=101°), the toe radius was smaller than the toe radius for the concave weld profile of the GTA welds (q=141°). The consequence of this is that the stress concentration at the weld toe of the GMA weld is more severe and one would expect the fatigue strength to be lower than for the GTA weld. However, the result is not seen here. The appearance of the GTA weld is misleading. It looks smoother than the GMA weld, however on a microscopic scale at the weld toe close to a weld pulse edge

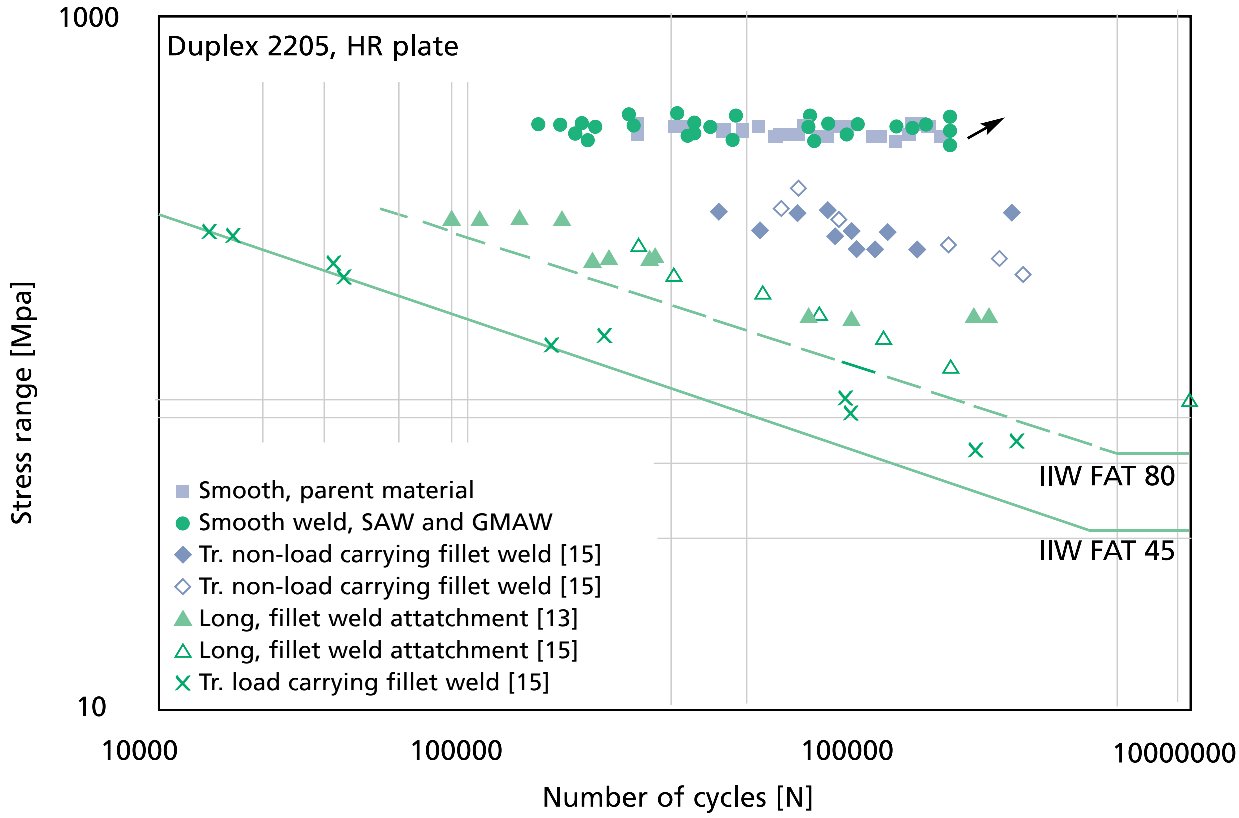

Figure 7: *Fatigue results for parent and welded duplex 2205, HR plate, 10–20 mm*

the radius is relatively sharp.

Furthermore, the FCA welded joints showed that although the openings at the weld root, the crack initiated in the weld toe. The FCA weld profile is concave (q=146°), resulting in the highest fatigue strength at a high number of cycles among the compared welding methods. However, at a low number of cycles the FCA welds are among the worst. One explanation could be that the FCA welds were welded in two sets giving slightly different geometry of the weld profile and besides that, they should have been welded with the same procedure. Some unknown factor has influenced the fatigue resistance of the joint. This variation shows the danger in looking at single set of data. In this case it is therefore chosen to illustrate all joints in the same diagram and judge them as one single group. All specimens of this group of load carrying fillet welds were better than FAT80.
It should also be noted that the IIW guideline is built up from testing of heavy plate about 10 mm.

Maddox et al [15] has recently presented results on cruciform joints in duplex 2205 (Figure 7) where he recommended fatigue class 36 for a joint failing in the weld throat. An IIW recommedation for C-Mn is 45 for a cruciform joint with weld root crack. The results are within the scatter band for C-Mn. Thus, a fairly conservative recommendation is given presumably due to scarce data available on this type of joint.

Raszmjoo [2] showed that data for cruciform joints of austenitic stainless steels fall within the scatter band for C-Mn steels and Maddox [15] confirmed these results (Figure 9).

Transverse non-load carrying fillet welds

Lihavainen-Niemi-Viherma [16] reported data on non-load carrying fillet welds in duplex 2205 (Figure 9). Maddox [15] has also reported data and a recommendation for using fatigue class 80, same recommendation as for C-Mn steels in as welded condition.

Rasmjoo [2] suggests that the joint classfication for C-Mn is

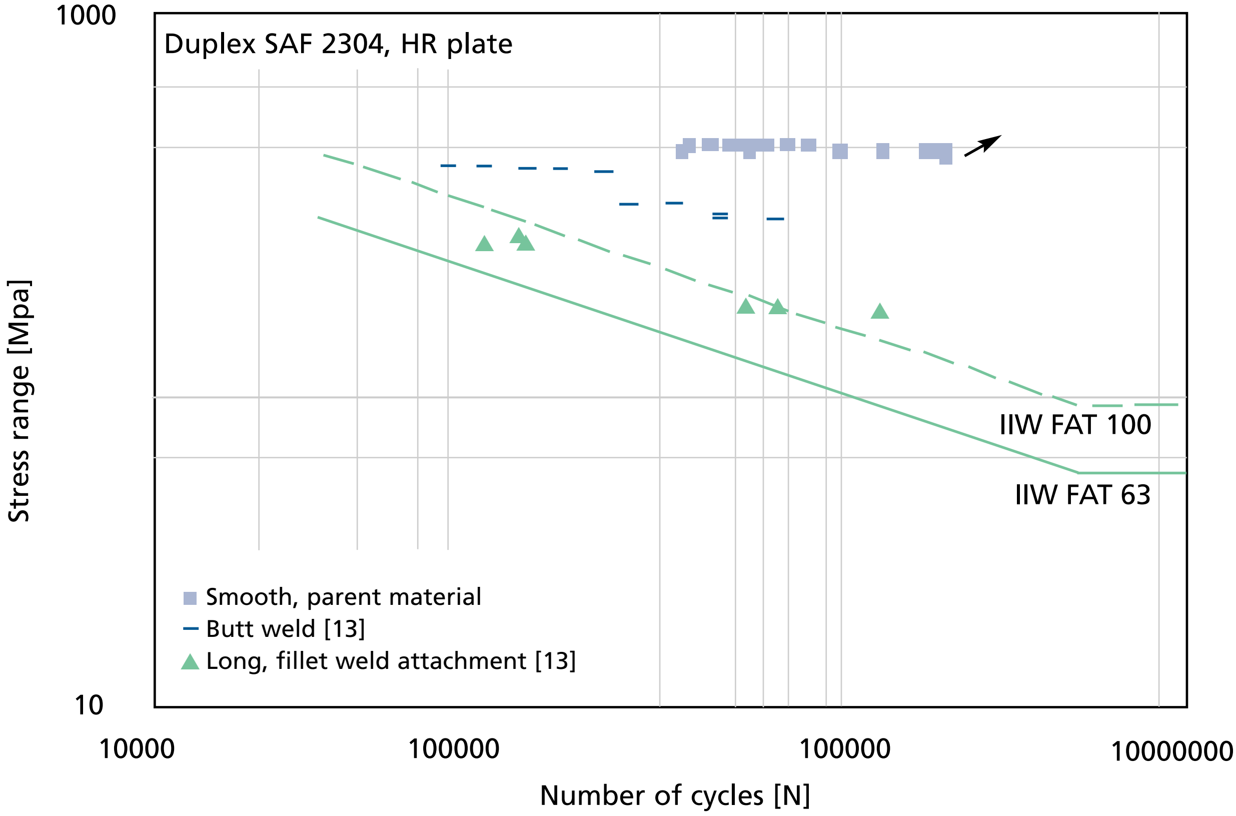

Figure 8: *Fatigue results for duplex 2304 and a similar (23Cr–4Ni) material, HR plate, 10–20 mm*

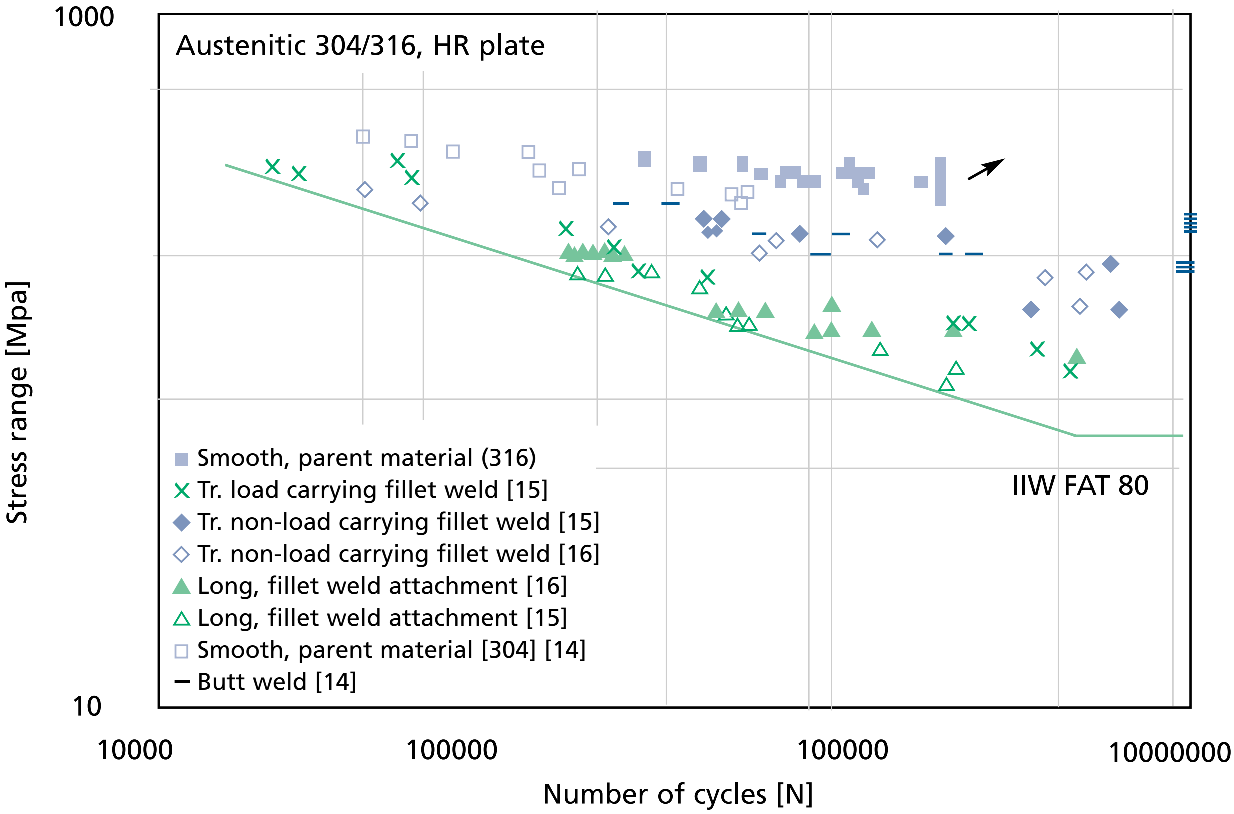

Figure 9: *Fatigue results for parent and welded austenitic steel 304/316, HR plate, 10–20 mm*

appropriate to use for austenitic steel based on the limited data available. Data for austenitic steels are shown in Figure 9.

Longitudinal fillet weld attachments

Data reported by Koskimäki-Niemi [13] for duplex steel (similar to 2304) indicate god results well above the recommendations for C-Mn, FAT63, for attachment length <300 mm. Maddox [15] and Viherma [16] reported data for duplex 2205 and they recommend the FAT71, i.e. the fatigue class when attachment length <150 mm for C-Mn steel.

Rasmjoo [2] concluded from reported data that austenitic steels give somewhat lower performance than C-Mn steel. However, data reported by Maddox [15] and Viherma [16] do not confirm this conclusion (Figure 9). Data are well above the FAT71 class.

Concluding remarks on fatigue design.

Until there is enough data to establish fatigue design guidelines for stainless steels the recommendations for C-Mn should be used. Even though, the results considered in this paper show superior fatigue strength to the fatigue classification for C–Mn steels (e.g. IIW, Eurocode 3), scatter in data have to be considered, as for C-Mn steels, which lower the recommended stress range. For further work it is also important to consider fatigue life improvement techniques e.g. TIG-dressing, influence of residual stresses and testing in corrosive environment.

As a comparison to the nominal stress approach results presented in this paper, Partanen and Niemi [17] reviewed hot spot stress approach results of welded details of both C–Mn and stainless steels. They concluded that fatigue class FAT100 or higher can be used as the design hot spot fatigue strength for toe failure of welded joints i.e. butt welds, transverse fillet welds, the ends of longitudinal fillet weld attachments of moderate thickness (<10 mm).

Conclusions

SMOOTH SPECIMENS

- Fatigue and corrosion fatigue properties have been assessed on smooth fatigue specimens for parent materials and welds of austenitic and duplex stainless steels.
- In air, the fatigue strength results showed a marked correlation with the tensile strength with a factor 2/3, i.e. close to the yield strength of the materials.
- Welds had a small effect on the fatigue strength for all steels in one set of tests (20 mm material). Multi-pass welds (GMAW, SAW) were at least on par with the base material for fatigue strength.
- For the thinner material (3 mm) the austenitic steel showed lower fatigue strength in spite of a higher tensile strength. The duplex base materials exhibited high fatigue levels. However welding with GTA, and in particular GMA, resulted in lower fatigue strength level than the base material.
- The welding methods tested appear to give comparable fatigue performance.
- In seawater environment (3% NaCl), the fatigue strength decreases 10% for the duplex 2205 grade and nearly 25 % for the austenitic 316L grade. The SAW welded materials were more resistant to corrosion fatigue than the parent materials.

FATIGUE DESIGN

- Results for butt welds and fillet welds have been included in design SN-curves showing the relation to C-Mn steels.
- Fatigue tests of welded structure show that stainless steels have superior fatigue life compared to the fatigue classification for C-Mn steels
- GTA butt welds of duplex stainless steels show surprisingly high fatigue strength
- The weld profile appears to have less than expected influence on fatigue performance for load carrying fillet weld of thin material (3 mm).

Acknowledgement

Parts of this research work (smooth welds) received financial support from European Coal Steel Commission (ECSC). Diploma workers, Magnus Piva and Ann-Jeanette Merilä, carried through the testing of as welded specimens.

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A new lean duplex stainless steel for construction purposes

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Introduction

Stainless steels are used predominantly for their corrosion resistance in moderate to highly aggressive environments. For construction purposes carbon steel normally has been the main choice of material due to low cost, long experience, applicable design rules and a large variety of strength classes. However, different stainless steel types can also provide a very wide range of mechanical properties and they have the apparent advantage of no need for surface protection. Examples are lamp-posts, handrails, storage tanks, vessels, etc.

Duplex stainless steels in particular, with twice the mechanical strength of conventional austenitic and ferritic stainless steels, have a potential for use in constructions. Since the introduction of this family of steels about seventy years ago these steels have been used in many structural applications. However, for various reasons, the primary motive for the selection a duplex grade has been towards the higher end of its excellent corrosion resistance in combination with its high mechanical strength. This is not surprising since they all contain a high level of chromium with inherently a good corrosion resistance.

The duplex grades have been improved during recent years (1). In the early 1980's a "second generation" of duplex steels was introduced with improved weldment properties mainly through nitrogen alloying (2,3). The most common duplex grade today is EN 1.4462 (UNS S31803/S32205) and this steel is used in a great number of applications in a wide variety of product forms. Parallel with the development towards higher alloy duplex grades for corrosive conditions there has recently been a great interest in leaner compositions for construction purposes. The best known commercial leaner duplex steel is EN 1.4362 (UNS S32304) with about 23% Cr and 4% Ni. As an example, this steel has been successfully used as a construction material of blast and firewalls on offshore platforms and in bridges (4). An apparent and frequently used way to further reduce the cost is to reduce the nickel content and compensate with manganese and nitrogen additions. Low nickel content will also reduce the influence of price fluctuations of raw materials. Such concepts were described already in 1970's but to our knowledge no commercial steel was produced at that time (5). In former Soviet Union several duplex steels with low nickel and high manganese were listed in 1970's but there was no information regarding their use. In 1989 an Armco patent was published on lean duplex steel thermally stable against transformation to martensite and with excellent as-cast properties. Thin-walled castings for automotive applications were mentioned (6). A commercial steel according to this invention, Nitronic 19D (UNS S32001), containing essentially 20% Cr, 5% Mn, 1.1% Ni and 0.13% N, was later proposed as modular frame material in a new automotive concept (7). Nitronic 19D has also been used for longitudinally welded umbilicals (8). Much work with low nickel duplex grades has been performed in South Africa. High manganese variants with some molybdenum and copper additions showed better corrosion resistance than EN 1.4462 in sulphuric acid (9). A spun-cast low nickel grade (RelyNite) with 21% Cr, 7% Mn and 0.35% N was developed for pit props in underground mining (10). Lean duplex alloys with low nickel content and manganese addition having a metastable austenite can be produced with interesting mechanical properties after deformation (11,12). However, as with temper rolled austenitic grades there is a risk of reduced strength of the welded area. Work with nickel-free, high manganese, high nitrogen duplex steels for structural engineering applications showed promising properties for a steel composition with 22% Cr, 10% Mn and 0.3% N (13).

As shown above there have been several low nickel, manganese-alloyed duplex stainless steels presented during the last decade. Depending on the property requirements, different alloying philosophies have been used. One important feature is the stability of the austenite. Transformation to martensite can result in very high mechanical strength but can also produce sensitivity to cracking under certain conditions. The objective of the present work was to develop a thermally stable, low nickel, general-purpose duplex grade with a corrosion resistance comparable to that of 1.4301 with undiminished weldment properties in the as-welded condition. In this paper a new grade, AvestaPolarit LDX 2101, meeting those requirements, will be presented.

Experimental

Pre-study of lean duplex alloys started with thermodynamic calculations for construction of phase diagrams and comparison by examinations of microstructure in small 0.5 kg ingots. The pre-study indicated that the most interesting ranges of main alloy elements in a lean duplex stainless steel were, C 0.03–0.05%, Mn 4–6%, Cr 21–22%, Ni 1.0–1.5%, Cu 0–1% and N 0.20–0.25%. Trials with this range of compositions were performed on 30 kg laboratory heats to further optimise the properties.

LABORATORY HEATS

Evaluations of hot and cold rolled plates were performed on material produced from the 30 kg ingots. The aim was to find a suitable composition that combined mechanical properties, corrosion resistance, structural stability and reforming capacity of austenite after thermal cycling, e.g. welding operations. The optimised composition based on the laboratory trials is shown in Table 1. The steel designation is AvestaPolarit LDX 2101

INDUSTRIAL HEATS

Several full-scale heats of LDX 2101 were produced, both in nearly square (bloom) section aimed for evaluation of long products as rod and bar and in various slab sections for manufacturing flat products such as plate, coil and sheet. All heats were conventionally produced, i.e., scrap re-melting in an electric arc furnace, refined in AOD/CLU converters and continuously cast. The weight of the casts was 75 to 90 tonnes. The casts made for long products were processed via a CLU (a proprietary process using steam-oxygen decarburisation) vessel.

The final products within the trials of long products included bar, rod and reinforcement bar in different dimensions. Most of those products were not subjected to solution annealing. In this paper, therefore, presentation of product properties is confined to various flat products. Annealing temperature was in the range 1020 to 1100°C followed by rapid cooling.

Different types of final products from the trials of coils and plate manufacturing are presented in Table 2.

C	Si	Mn	Cr	Ni	Mo	Cu	N
0.03	0.7	5.0	21.5	1.5	0.3	0.3	0.22

***Table 1:** Typical chemical composition for LDX 2101 in w-%. Fe bal.*

Products	Dimensions (mm)	Surface finish (EN code)
Hot rolled plate & coils	t: 4 – 65 w: 1400 – 2000	1D
Cold rolled coils	t: 1 – 4 w: 1280 –1400	2D, 2E, 2R

***Table 2:** Flat product forms in the trials*

Industrial trials of manufacturing of longitudinally welded pipes from 9 and 16 mm thick hot rolled plate were also performed, as well as rectangular hollow sections made from coil with a thickness of 3 mm.

Results

MICROSTRUCTURE

A balanced chemical composition in LDX 2101 results in a microstructure containing approximately equal amounts of ferrite and austenite. This is obtained after annealing at a temperature of about 1050°C. Due to its relatively low alloying content of substitution elements, this lean grade is less sensitive to segregation during solidification than standard duplex and superduplex grades. The relatively low chromium and molybdenum contents make precipitation of intermetallic phases more sluggish than in conventional duplex steels. This can be shown by the influence of isothermal heat treatment on the impact toughness. In Figure 1, a Time–Temperature-Charpy V (T-T-ChV) diagram for two duplex grades are shown. The most sensitive temperature range for LDX 2101 is 600 to 750°C. At the nose temperature, ~650°C, about 10 hours isothermal annealing is needed to reduce the impact strength to 50J and almost 100 hours to 27J. For 1.4462 the embrittlement transition is much faster with a nose temperature of about 850°C and only about 15 minutes to reduce the impact toughness to 27J.

The position of the nose, regularly associated with intermetallic phase precipitation, is moved to a lower temperature compared to that for regular duplex steels. Lower temperature means reduced diffusion and thereby a retarding effect on precipitation. Figure 1 shows that LDX 2101 has a far better structural stability than the standard duplex stainless steels such as 1.4462.

MECHANICAL TEST

All products were tensile tested in accordance with the standard procedures in EN and ASTM. In Table 3 typical values for different flat products are presented; hot rolled plate (HRP), white hot band (WHB) and cold rolled sheet (CR). Brinell Hardness measurements are also included. The materials are in a solution-annealed condition.

CORROSION TESTS

Intergranular corrosion tests according to EN/ISO 3651-2 method A (Strauss) and method C (Streicher) were made on several LDX 2101 products. None of the samples failed in the tests. These results are as expected for duplex steels, which are less susceptible to this kind of corrosion than austenitic stainless steels.

All flat products were also tested regarding chloride pitting corrosion resistance by using the

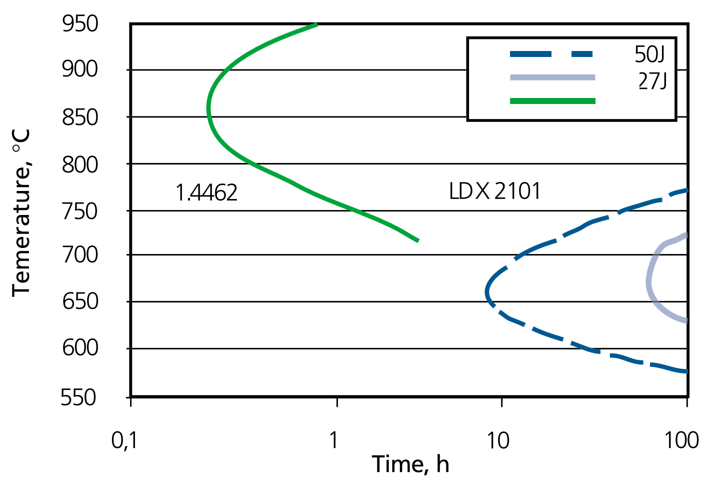

Figure 1: *GT-T-ChV-diagram for 1.4462 and LDX 2101 plate materials (15 mm).*

	$Rp_{0.2}$ (MPa)	Rm (MPa)	A_5 (%)	HB
HRP, 15 mm	480	700	38	225
WHB, 4 mm	570	790	38	230
CR, 1 mm	600	840	40	230

Table 3: *Typical mechanical properties at 20°C for different flat products of LDX 2101*

Avesta cell (ASTM G150). The outcome in the determinations of critical pitting temperature (CPT) varied between 15 and 22°C, depending on the surface condition. This level is higher than what is normally obtained with EN 1.4301 and more on par with the results for EN 1.4401.

A number of different test methods were used to assess the susceptibility of LDX 2101 to stress corrosion cracking (SCC). Specimens were stressed according to the four-point loading practice in ASTM G39, and exposed to a 3.6 M calcium chloride solution as well as a 3 M magnesium chloride solution. In both cases the tests were done at 100°C for 500 hours. The specimens were loaded to 60 and 90% of the proof strength at 100°C. U-bend tests in a 3 M magnesium chloride solution were also performed with the bending parallel and perpendicular to the rolling direction. The temperature and duration were the same as for the four-point tests. The LDX 2101-material passed all the SCC tests without failure due to cracking. However, many samples in the tests got some kind of superficial uniform corrosion attack.

Uniform corrosion tests in different concentrations of sulphuric acid and temperatures were made. The result of the test is presented in an isocorrosion diagram, Figure 2, where the curves are representing a corrosion rate of 0.1 mm/year. At temperatures above the curves the corrosion rate is greater than 0.1 mm/year. For reference the austenitic stainless steel grades 1.4301 and 1.4436 plus the duplex grade 1.4362 are included in the figure.

WELDING TRIALS

Manufacturing trials of longitudinally welded pipes and tubes were made. Pipes with the size OD 273 x 9 mm and OD 273 x 16 mm and length of 6,000 mm were made. Welding methods for the longitudinal pipe welds were plasma arc welding (PAW), gas tungsten arc welding (GTAW). For the thicker wall, submerged arc welding (SAW) was used to fill up the joint. All weld beads were performed with filler of 2209-wire except for the first keyhole PAW-pass. The pipes were post-weld solution annealed at 1050–1070°C and pickled in mixed acid. Tensile samples taken transverse to the weld joints were tested. All ruptures on the tensile samples occurred in the parent material. The ultimate tensile strength was 30 to 40 MPa higher than for the parent plate material. 1.4362 are included in the figure.

Impact toughness testing, Charpy-V, was performed transverse to the welds and with the notches placed in the weld metal and in the parent material next to the weld metal. The test temperature was –50°C. The impact result for the pipe with 16 mm wall thickness, welded with SAW was 47 J in the weld metal and 54 J next to the weld. The impact values are on the same level as the base material as shown in Figure 3 with the ductile to brittle transition curve for the plate material before manufacturing of the pipes. Compared with other duplex stainless steels with nickel contents in the range of 6 to 8%, this low nickel grade appears to have a lower upper shelf value. However, the transition behaviour and lower shelf values are similar to that of standard duplex alloys.

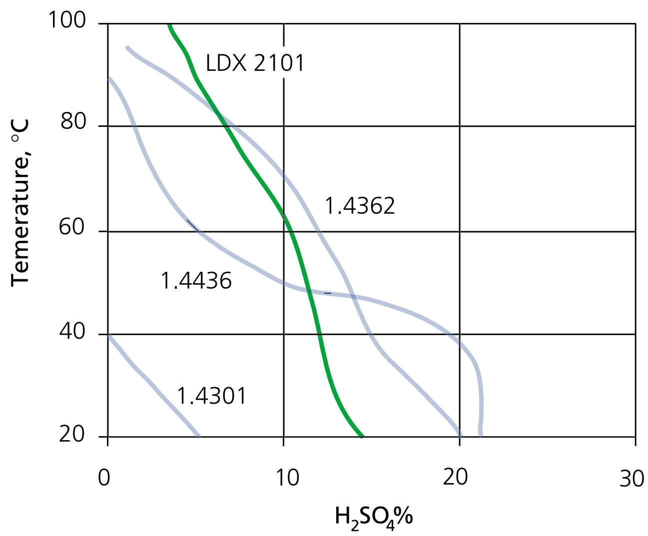

Figure 2: *Isocorrosion curves for LDX 2101 and other steels with a rate of 0.1 mm/y in H_2SO_4-solution.*

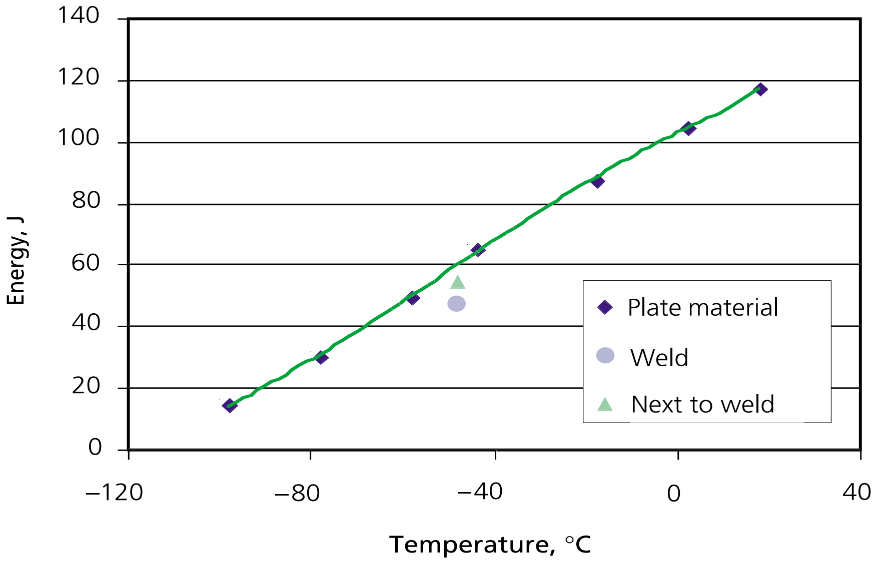

Figure 3: *Impact toughness of LDX 2101. Ductile to brittle transition curve for 16 mm thick hot rolled plate and of seam weld in pipe produced of the plate.*

Manufacturing trials of rectangular hollow sections were made at Stala Tube Oy in Finland. The hollow section was produced out of coil in a continuous line for forming and welding to a section of 140x80x3 mm followed by cutting to length. The continuous welding in the line was performed with PAW keyhole technique, followed by a GTAW-dressing of the weld cap. The welding was made without filler and with a duplex 2209-filler. No annealing of the hollow sections was made.

The weld ductility in the hollow sections was evaluated by U-bend tests. Samples welded with filler and without filler were taken across the weld. 180° bending was performed with both the weld cap and the weld root out over a mandrel with a diameter of 16 mm. All samples passed the test without cracking.

Microstructure examination of the welds in the hollow sections showed that the reforming of austenite in the weld metal and in the heat affected zone is very fast. The fast forming of austenite is controlled by the nitrogen alloying in LDX 2101. Figure 4 shows the microstructure of an autogenous PAW joint without any post weld heat treatment. The total arc energy was 1.3 kJ/mm. The ferrite content was determined by image analysis to 61% in the weld metal, 64% in HAZ and 49% ferrite in the parent material.

Practical implications

The property profile of LDX 2101 shown in the previous sections is to great extent typical for a second-generation duplex stainless steel. With comparatively high nitrogen content the mechanical strength is on level with that of type 1.4462 and also on level with those of several quenched and tempered steels. The weldment properties, also due to the nitrogen level, seem to be excellent even when welding without filler. This indicates that the material can be welded without the close restrictions necessary for many other duplex grades. Ongoing work in this area will produce more data in this respect.

Other specific features of this lean duplex grade are the very high structure stability. Due to the low nickel content this steel has somewhat reduced impact toughness of the base material compred to standard duplex steels.

Altogether, the property profile of LDX 2101 shown in this paper indicates that it has a potential for use in a large variety of applications. However, for use

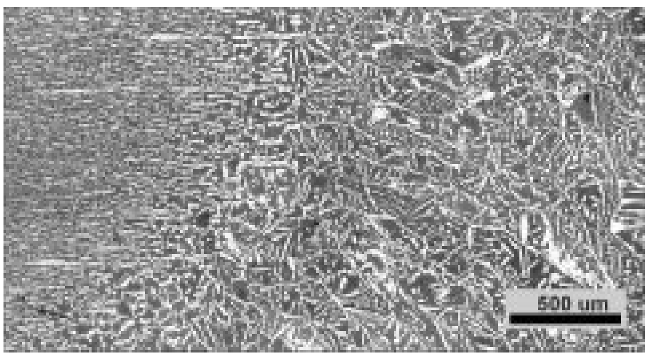

Figure 4: *Microstructure in an autogenous PAW joint in a rectangular hollow section of LDX 2101. Beraha etchant.*

Figure 5: *The Apaté-bridge at Sickla channel in the centre of Stockholm. Bridge made of DSS (1.4462) under construction. (Created by Magnus Ståhl & Erik Andersson)*

as a stainless structural steel, further documentation is needed. Fatigue testing of parent material as well as welded joints is one area being evaluated at present. It is also important to get such steels included in construction standards.

Below, some potential application areas for LDX 2101 are discussed.

A fairly new area where duplex stainless steels are used is the construction of bridges. The materials choice is based on the high strength and low maintenance and life cycle cost but strong reasons are also environmental concern and aesthetic values. An example where this has been utilised in a new design, with duplex steel as load-carrying structural material, is shown in Figure 5.

Several other applications in the civil engineering area are components needing high mechanical strength and corrosion protection, equipment that today is made of high strength, galvanised or painted carbon steels.

Stainless steels, including duplex, are already being used as reinforcement bar material in concrete structures to improve the service life in chloride-contaminated environments. Having a high structural stability, LDX 2101 is possible to produce in as hot rolled condition with adequate property profile; high strength, good corrosion resistance.

Storage tanks and towers with modest requirements on corrosion resistance is another example where LDX 2101 has an advantage compared to 1.4301 and 1.4401 due to the high strength giving weight savings.

Duplex stainless steel is a potential material and used construction material for transport applications. For train carriages certain components where high strength and low maintenance cost is required, LDX 2101 is a good alternative.

Other applications were LDX 2101 has an advantage is in water heaters and hot water tanks due to the fact that duplex stainless steels have a high resistance to stress corrosion cracking.

Conclusions

A new lean duplex stainless steel, AvestaPolarit LDX 2101, designed for construction purposes is presented.

- Full-scale manufacturing experience has been made with a great variety of products, including hot rolled plate, coils in different surface conditions, seam welded pipe, seam welded hollow section, bar, rod and reinforcement bar.
- Low nickel content combined with manganese and nitrogen additions gives the steel a high structural stability.
- Low nickel content also gives less sensitivity to price fluctuations.
- Mechanical strength is high, on a level with other duplex steels and also with age-hardening steels.
- The corrosion resistance of LDX 2101 is in general at least as good as 1.4301 and in most cases as good as 1.4401.
- The weldability, even without filler addition is very good giving excellent weldment properties in as-welded condition.

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acom is distributed to persons actively involved in process industry development and other areas where stainless steels are important.

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