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Evaporators Made of Duplex Stainless Steel A New Approach to Reduced Costs

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Abstract. Evaporators in big MSF-plants have traditionally been made of mild steel which should be corrosion resistant enough to cope with an environment of de-aerated seawater. However, experiences have proven that the environment is not always free of oxygen and corrosion has frequently occurred, especially during shut-down periods. One consequence is that a corrosion allowance has to be added and yet, protective layers in form of epoxy coatings and metallic linings are applied. Another alternative is to use solid stainless steel for the evaporator vessels. This paper will discuss the possibility of using two grades of ferritic-austenitic, or duplex, stainless steel for evaporators.

Introduction

Evaporators in big MSF-plants have traditionally been made of mild steel which should be corrosion resistant enough to cope with an environment of de-aerated seawater. However, experiences have proven that the environment is not always free of oxygen and corrosion has frequently occurred, especially during shut-down periods. One consequence is that a corrosion allowance, sometimes in the range of the originally required wall thickness, has to be added and yet, protective layers in form of epoxy coatings and metallic linings are applied.

Also external surfaces have to be painted and later on also maintained in order to prevent extensive rusting. Another alternative is to use solid stainless steel for the evaporator vessels. This paper will discuss the possibility of using two grades of ferritic-austenitic, or duplex, stainless steels for evaporators.

The use of these stainless steels, Avesta Sheffield 2205 and SAF 2304 (ASTM/UNS S31803 and S32304 respectively) will result in far lighter and more corrosion resistant evaporator vessels lowering investment and maintenance costs.

The chemical compositions of S32304 and S31803 are given in Table 1 together with some other stainless steels discussed.

Table 1. Typical chemical compositions (% by weight) of the stainless steels discussed

Steel grade	C	C_r	N_i	M_o	N
254 SMO®/S31254	0.01	20	18	6.1	0.2
904L/N08904	0.01	20	25	4.5	0.06
2205/S31803	0.02	22	5.5	3.0	0.17
317L	0.02	18.5	13.5	3.2	0.08
316	0.04	17	11.5	2.2	0.06
SAF 2304™/S32304	0.02	23	4.5	0.3	0.10

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Corrosion resistance

The corrosion hazards for stainless steel when expoed to hot seawater are pitting, crevice corrosion, and stress corrosion cracking (SCC). Pitting and crevice corrosion are more common at ambient and slightly elevated temperatures, while SCC occurs predominantly at temperatures from just below 100°C.

The resistance to pitting and crevice corrosion is determined by the contents of chromium, molybdenum, and nitrogen and the relative influence of these alloying elements is sometimes described in a Pitting Resistance Equivalent (PRE) formula [1].

$$PRE = \%Cr + 3.3 \times \%Mo + 30 \times \%N$$

Calculated PRE-values and critical pitting temperatures (CPT) for the stainless steels discussed are given in Table 2. One important aspect is the nitrogen content of S31803, which, according to a number of national standards, can vary between 0.08 and 0.20%. A high nitrogen level, preferably above 0.15%, does not onbly improve the corrosion resistance of the base material as shown in Table 2, but it also improves the pitting resistance and toughness of the heat affected zone after welding [2,3].

The resistance to SCC is improved by, either a high content of alloying elements in general and nickel in particular of an austenitic steel like S31254, or by the intro-

Table 2. Pitting resistance equivalents (PRE) and critical pitting temperatures (CPT) for some stainless steels

Steel grade	PRE	CPT, °C*
S31254	46	90
N08904	36	61
S31803, high N	38	54
S31803, low N	36	46
317L	30	28
316	25	16
S32304	26	19

*Determined in a 1M NaCl solution [4,5,6]

duction of ferrite in the structure. Consequently ferritic-austenitic stainless steels are vastly superior to a conventional austenitic grade like 316, see Table 3.

Table 3. SCC in sodium chloride as determined by the drop-evaporation test at approximately 100°C [7,8].

	Applied stress		Time to failure	
Steel grade	% × $R_{p0.2}$*	MPa	hrs	
316	10	21	155	158
S32304	50	181	467	470
S31803	50	229	360	>500
S31254	90	221	>500	>500

*$R_{p0.2}$ being the 0.2% offset yield strength at + 200°C

From these tests results the following conclusions can be drawn:

- The lean duplex grade S32304 has approximately the same resistance to pitting and crevice corrosion as 316.
- The duplex grade S31803 is superior to 316 and 317L and very close to the highly alloyed grade 904L, but only if specified correctly, i.e. with a high nitrogen level.
- Both duplex grades have a high resistance to SCC and will probably withstand the conditions inside and outside an MSF-chamber.

Mechanical and Physical Properties

All duplex stainless steel have high strength than conventional austenitic grades, the proof stress is between 2 and 2.5 times as high, and they are also stronger than carbon steel used for evaporator vessels in MSF-plants, see Table 4.

The thermal expansion of a duplex stainless steel is closer to that of carbon steel, like BS 43b, than that of 316, Table 4.

Table 4. Relevant mechanical (minimum values) and physical properties of steels for evaporator vessels

Properties	BS 43b	S32304	S31803	316
$R_{p0.2}$, MPa	260	400	450	205
R_m^*, "	485	600	620	510
A_5^*, %	20	25	25	45
Thermal expansion, × 10^6	11	13	13.5	16.5

* R_m is the ultimate tensile strength and A_5 is the minimum elongation at fracture.

The conclusion is that evaporator vessels made of duplex stainless steels can be redesigned in thinner sections than those used in carbon steel. Furthermore, the risk of thermal fatigue of welded joints between stainless steel and mild steel is reduced due to the similar thermal expansions.

Design

Wall thickness

This section will show how the choice of steel grade affects the thickness of the outer shell of the evaporator vessel. The following conditions have been assumed:

- The outer shell of the evaporator vessel is fabricated from flat plate with thickness t [mm], stiffened by outstanding stiffeners with a spacing of b [mm].
- The width of the vessel, a, is much greater than the stiffener spacing, b. for this design the spacing between the stiffeners is important and this spacing governs the plate thickness to be used.

Material data at 100°C according to Table 5. (Data for the normal maximum operating temperature in the vessel of 120°C is very close to this.) The allowable stress, σ_{all}, in the vessel used in this example is $\sigma_{all} = R_{p0.2}/1.5$, with 1.5 being the safety factor.

The loading condition is full vacuum in the vessel. Relationships for the stress in the plate are given by Young [9] and the maximum stress, σ_{max}, that occurs can be calculated, using:

$$\sigma_{max} = -\frac{0.5 \times q \times b^2}{t^2}$$

where q = distributed load, b = stiffener spacing and t = sheet thickness.

Table 5. Material data at 100°C for the grades studied

Material data	43b	S32304	S31803	316
$R_{p0.2}$, MPa	201	315	360	175
σ_{all}, MPa	134	210	240	117
E* MPa	200000	190000	190000	190000

* E is the Young's modulus of elasticity.

The maximum deflection, Δ_{max}, in the plate between the stiffeners is obtained by:

$$\Delta_{max} = \frac{0.0284 \times q \times b^4}{E \times t^3}$$

when σ_{max} equals σ_{all} the corresponding plate thicknesses are given in Table 6 for a stiffener spacing of b = 500 mm.

Table 6. Plate thickness and maximum plate deflection for a stiffener spacing of 500 mm

Grade	43b	S32304	S31803	316
t, mm	9.7	7.7	7.2	10.4
corr. allow., mm	5.0	–	–	–
t_{tot}, mm	14.7	7.7	7.2	10.4
t_{tot}/t_{tot}43b	1.00	0.52	0.49	0.71
Δ_{max}, mm	0.9*	2.0	2.5	0.7

* without corrosion allowance

The use of duplex stainless steel enables a wall thickness reduction of 50 % when compared to carbon steel. The corresponding figure for 316 is 30%. If thinner plates are being used, the deflections become greater, from roughly 1 mm for the carbon steel to 2.5 mm for S31803. This increase in deflection is not supposed to cause any problems.

No effects of welds have been accounted for in the analysis. Welds occur in the most unfavorable locations where the stresses are at maximum. It would be much better, from a structure design point of view, to have the stiffeners on the inside of the vessel, but that may not be possible in practice.

Stiffeners

The vessel is supported by stiffeners with a length of 'a' and a spacing of 'b'. Many different design are used when applying these stiffeners and no specific design will be made in this paper. However, there is a possibility reducing the thickness of the stiffeners if a profiled section is used. This reduction in thickness is linearly proportional to the increase in design stress, as shown in Table 7.

Table 7. Thicknesses ratios for profiles used as stiffeners

Grade	BS 43b, mild steel	S32304	S31803	316
Ratio	1.0 (ref)	0.64	0.56	1.15

From Table 7 it can be noted that the duplex grades give a great reduction in the thickness needed. If the thickness is reduced, the risk of localized buckling of the stiffener increases. This may, though, be avoided by changing the design of the stiffener by introducing "local stiffening" with grooves or wrinkles.

Economy

One driving force for the selection of material and design is the eagerness to keep the costs down. Costs should not be looked upon as investment costs only but maintenance costs and production losses should be included as well. A life cycle cost concept should be applied.

The example given in the previous section can be further developed into a cost model where different costs like the purchase of material, fabrication, painting etc. are included. The calculations below are based on a simplified flash chamber shell in the form of a box with the following dimensions:

- Width 4m
- Height 3 m
- Length 15 m

Table 8 contains a summary of costs when building this simplified flash chamber shell.

Table 8. Different costs for the fabrication of a simplified flash chamber shell in mild steel or stainless steel

	C-steel	S32304	S31803	316
Material				
Weight, kg	26830	14054	13141	19469
US$/kg	0.50	2.80	3.25	2.65
Cost, US$	13415	39351	42708	51590
Fabrication, US$	48000	38700	38700	38700
Lining				
Area, m^2	117			
US$/$m^2$	200			
Cost	23400			
Painting				
Area, int., m^2	117			
US$/$m^2$	45			
Area, ext., m^2	234			234
US$/$m^2$	25			25
Cost	11115			5850
Total, US$	95930	78051	81408	90290

The costs are based on the following information:

- Steel price, Avesta Sheffield AB
- Fabrication, St°almonteringar, Trollhättan, Sweden (mechanical workshop).
- Living with 3 mm 316 sheet, Berglunds Rostfria, Boden, Sweden (mechanical workshop).
- Painting, ÖMV, Örnsköldsvik, Sweden (mechanical workshop), paint thickness based on information from the Swedish Corrosion Institute (200 μm externally and 300 μm internally).

The cost for external stiffeners has not been included but a number of different technical solutions and consequently also cost levels can be considered.

- Stainless stiffeners in S32304 or S31803 enable thickness reductions which partially balance the more expensive material and welding costs.
- Carbon steel stiffeners can also be applied on stainless steel shells but partial or total external painting is then required.

The obvious conclusion from this section is that a flash chamber shell made of solid duplex stainless steel will be considerably cheaper than a corresponding one made of carbon steel with internal lining and coating.

External stiffeners made of stainless steel will be more costly than carbon steel. If this cost increase is high enough to prevent the use of stainless steel stiffeners there is still the possibility of using carbon steel stiffeners on the stainless shell. The cost benefit in the solid stainless shell will also cover the penalty of external painting.

Experiences

There is no information available about previous use of solid duplex stainless steels in flash chambers but solid, highly alloyed austenitic stainless steel has successfully been used at Sirte, a 10 000 m^3 /d MSF-plant in Libya [10].

However, there are many examples of duplex stainless steel installations elsewhere. Pressure vessels in form of kraft digesters for the pupl industry have been in service since 1988. These digesters are typically designed for a pressure of 15 bar and a temperature of 200°C. The switch from carbon steel to S31803 has enabled a wall thickness reduction from above 40 mm, corrosion allowance included, to 15-20 mm [11]. Experience of the use of duplex grades within the pulp & paper industry is in general good, “they have become an almost automatic maintenance replacement of failures of austenitic stainlesses” [12].

The high strength has also been utilized for non-pressurized storage tanks in phosphoric acid plants and breweries enabling weight and cost reductions of 34% and 6% respectively when compared to conventional austenitic grades [11].

A third type of application is for chemical tankers where S31803 has been utilized for the stainless steel tanks in more than thirty ships. The biggest tanks have a loading capacity of more than 1000 m^3 and the biggest ships are of the size of 12000 dwt.

However, the most commonly utilized applications are for offshore pipe lines, where type S31803 is the obvious replacement for carbon steel or low alloyed steel when the hostility of the environment becomes too severe.

Conclusions

1. By utilizing the strength and the corrosion resistance of the two duplex stainless steels S32304 and S31803 when designing evaporator vessels in MSF-plants, it is possible to construct these lighter and cheaper than if being made of carbon steel.
2. The two different levels of corrosion resistance enable the selection of a grade with a performance either similar to that of 316/316L or very close to that of type N08904.
3. Experiences from fields of application other than desalination have shown that duplex stainless steel can be the cost effective alternative not only to carbon steel but also to conventional austenitic stainless steels like 316/316L.

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المُبَخِّرات المصنوعة من الفولاذ المزدوج المقاوم للصدأ
اتجاه جديد لتخفيض التكلفة

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ملخص البحث. تصنع المُبَخِّرات التي تعمل في محطات التحلية الكبيرة ذات التبخر الومضي عادة من الفولاذ الطري التي يجب أن تكون ذا مقاومة للتآكل لتواكب بيئة المياه المُزال منها الهواء ومع ذلك فإن الخبرة أثبتت أن البيئة لا تكون خالية دائمًا من الأكسجين ولذلك يحدث التآكل تكرارًا وخاصة خلال فترات توقيف المحطة ولذلك فإنه يزداد سمك المعدن ويغطى المعدن بطبقات واقية من الأبوكسي والمعدن.

ويوجد هناك طريقة أخرى وهى استعمال فولاذ مقاوم للصدأ للمُبَخِّرات وتُناقش هذه المقالة إمكانية استخدام نوعين من الفولاذ المزدوج المقاوم للصدأ.