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Digesters and Pulp Storage Towers of Duplex Stainless Steels-Saving Weight and Costs

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Abstract

Austenitic stainless steels, often clad on carbon steel, have for many years been used as construction materials for digesters and pulp storage towers in order to reduce maintenance costs resulting from corrosion. Another option is to use a solid high-strength duplex (ferritic-austenitic) stainless steel. This approach provides the combined advantages of low maintenance and reduced material requirements for the initial investment.

For pressure vessels, the superior strength of a duplex stainless steel, UNS S31803, makes it possible to obtain wall thickness reductions of up to 46%.

Savings can also be obtained by using duplex steels for non-pressurized vessels, e.g. a pulp storage tower. Calculations covering costs of both material and work show that a solid duplex stainless steel tower using UNS S32304 might yield cost savings of 8% compared to a tower of carbon steel lined with austenitic stainless steel.

Both these duplex grades have better corrosion resistance than carbon steel in kraft digester environments, and are also more resistant in washing, black and green liquors. Field tests have also shown that S31803 resists corrosion in sulphite digester environments better than AISI types 316L and 317L

Duplex Stainless Steels

Duplex (ferritic-austenitic) stainless steels have been the object of increased attention during the last decade. Conferences devoted entirely to this type of steel are held regularly. This growing interest is perhaps a reflection of the increasing number of grades available, but this type of steel is in no way a recent development. Duplex grades have been produced in Sweden since 1930.

The properties of early duplex grades limited their use mainly to unwelded construction and castings. Many problems with structural stability, corrosion resistance, etc. remained until the 1970's, although plate and forgings of the duplex grade 453S (similar to AISI type 329) were successfully welded together to form coolers of Brobeck type for the pulp industry as early as in 1932. Since then many new grades have been developed, making the usefulness of this group of steels comparable to that of the traditional austenitic family (1).

The duplex stainless steels of today are produced in a full range of product forms. They are readily welded and machined. Furthermore, duplex steels cover virtually the same wide range of corrosive environments as austenitic grades. The major difference between these two types of steel is the considerably higher mechanical strength of duplex grades compared to that of austenitic grades with comparable corrosion resistance.

Table 1.
Typical chemical compositions of some duplex and austenitic grades.

Steel grade Trade name	ASTM	Chemical composition, wt% C	Cr	Ni	Mo	N	Structure
453S	(329)	0.08	26	5	1.5	0.05	duplex
SAF 2304™	S32304	0.02	23	4.5	-	0.10	duplex
2205	S31803	0.02	22	5.5	3	0.15	duplex
304L	304L	0.02	18.5	9.5	-	0.06	austenitic
316L	316L	0.02	17	11.5	2.2	0.06	austenitic
317L	317L	0.02	18.5	13.5	3.2	0.08	austenitic

SAF 2304 is a trademark owned by Sandvik AB and used by Avesta Sheffield AB.

Chemical Composition

Table 1 shows the typical chemical compositions of two modern duplex grades. For comparison, the compositions of the duplex grade from 1932, 453S, as well as some austenitic grades have also been included.

Corrosion Resistance

Duplex grades offer corrosion resistance to many different types of environments, and the resistance to localized attack is in many cases of crucial importance. Determining the critical pitting temperature (CPT) of the steels in a chloride solution will give quite a good ranking of the grades in this respect. Table 2 shows CPT values determined according to two different methods, one based on testing in 6% $FeCl_3$ and one in 1M NaCl. The table also illustrates that the resistance of the duplex grade S32304 to localized attack is not inferior to that of 316L and that S31803, another duplex grade, can be expected to perform slightly better than 317L. Steel grades with even higher corrosion resistance are also available, both austenitic grades and duplex, but these grades are usually of little interest when discussing digesters and pulp storage towers.

Mechanical Strength

The mechanical strength of duplex stainless steels is generally very high, as shown by Table 3. The yield strengths and the ultimate tensile strengths of these grades are considerably higher than corresponding strength values for austenitic grades of comparable corrosion resistance.

Table 2.
Resistance to pitting, typical values.

Steel grade	CPT in 6% $FeCl_3$, °C	CPT in 1M NaCl, °C
304L	~0	~0
316L	<5	15
S32304	20	15
317L	35	40
S31803	40	50

Table 3.
Mechanical properties (minimum strength values refer to the corresponding internal company standard).

Steel grade	Mechanical properties at 20°C, min values $R_{p0.2}$, MPa	R_m, MPa	A_5, %
304L	190	480	45
316L	210	490	45
317L	220	490	40
S32304	400	640	25
S31803	480	680	25

Weldability

Welding of modern duplex grades is not significantly different from welding austenitic grades. So far, the most frequently used methods have been gas tungsten arc, shielded metal arc, and submerged arc welding. Other useful methods are plasma arc, gas metal arc, and flux-cored wire welding. Neither preheating nor post weld heat treatment is normally necessary. When welding duplex stainless steels, filler metal must be used to obtain the correct ferrite-austenite balance. Normally an arc energy of 0.5-1.5 kJ/mm is used. Too low a heat input might increase the ferrite content and reduce both the corrosion resistance and the impact strength, especially when welding thick plate. It is advisable to let the material cool to below 150°C between passes. Extremely rapid cooling, e.g. in a tack weld, in spatter or in a strike mark, can lead to an unfavourably high ferrite content. Serious suppliers of base material and welding consumables can provide more detailed advice on methods to avoid weld defects (2).

The weldability of this group of steels can be summarized by quoting representatives of one large pulp and paper industry group (1): "Any welder competent to weld austenitic stainlesses will make a good weld in most duplex steels if the correct heat input and filler metal are used. Welding costs are no different than for the austenitics except for a slightly higher price per kg for filler metal. This applies to both shop and field welding".

Table 4.
Coupon testing for eight months in a sulphite digester, two-stage cooking, Na-base.

Steel grade	Corrosion rate mm/year	Remarks
316L	0.011	Slight etching under deposits, shallow pits under crevice washers, max 0.10 mm.
317L	0.009	Slight etching under deposits, shallow pits under crevice washers, max 0.10 mm.
S31803	0.005	Slight etching under deposits, max 0.04 mm.

Table 5.
Coupon testing for ten months in a sulphite digester,
Mg-base.

Steel grade	Corrosion rate mm/year	Remarks
316L	0.07	Slight etching under crevice washers, max 0.06 mm.
317L	0.13	Slight etching under crevice washers, max 0.04 mm.
S31803	0.06	Slight etching under crevice washers, max 0.02 mm.

Why Use Duplex Stainless Steels for Digesters?

Corrosion Design Aspects

As in many other harsh environments, stainless steels have become the obvious choice for sulphite digesters because the use of cheaper materials often results in extensive maintenance costs. Ordinary carbon steels and lower alloyed stainless steels will corrode severely in sulphite cooking acid. Not until the molybdenum-alloyed stainless steels were developed was it possible to find a construction material which could cope with both the corrosive environment and the high pressure in the digesters. These 316-type grades were called "acid-proof" because of the high resistance towards the cooking acid. In order to reduce investment costs, 316L and 317L digesters are often produced from clad steel, or from solid stainless steel in the cold-stretched condition.

The main reason for choosing a duplex grade when building a sulphite digester is that this material is at least as corrosion resistant as the austenitic alternatives 316L and 317L. Results from in-plant testing of welded coupons in two sulphite digesters are summarized in Tables 4 and 5. As can be seen in the tables, the duplex steel S31803 performs even better than 317L. From a corrosion point of view, these results lead to the conclusion that the duplex grade S31803 should be chosen, at least for the interior, when building sulphite digesters.

It is true that corrosion rates in sulphate digesters cannot be compared to the corrosion rates of the same material in a sulphite digester, and at some mills producing sulphate pulp, one might actually consider the corrosion rate of carbon steel as acceptable. But the potentially hazardous effects of corrosion of carbon steel in sulphate environment were emphatically demonstrated when the top of a digester in Pine Hill, AL, USA, blew off in 1980. Since then sulphate digesters around the world have been thoroughly inspected, and cracks have been found to be very common, in both digesters and pressure impregnation vessels made of solid carbon steel or carbon-manganese steel. The cracks are believed to arise from both hydrogen embrittlement, possibly caused by improper welding, and alkaline stress corrosion cracking. No cracks have been found in stainless steel digesters and impregnation vessels (3).

To prevent corrosion, impregnation vessels and the cooking part of continuous digesters are usually made of clad steel, mainly 304L for the stainless interior. However, cracks have also been found in the washing zone of some carbon steel digesters (3), suggesting that the entire digester should be made in stainless steel. However, cracking is not the only corrosion problem; carbon steel digesters also suffer pitting and general corrosion (3). These problems have been found to be more severe in batch digesters, probably due to the continuous changes in temperature pressure, etc, during operation (4). A consequence of this has been a widespread use of austenitic stainless steels (overlayed, clad or solid, sometimes cold-stretched) for batch digesters even for sulphate cooking.

The difference among the performances of different materials in a sulphate digester can be considerable, and the corrosion rate of carbon steel might reach several millimetres a year, as shown in Figure 1 which presents results from laboratory testing in simulated white liquor (5). All stainless steels included in this diagram can be regarded as resistant, but the lowest corrosion rates are shown by the duplex grades, S32304 and S31803. Composition of the simulated white liquor is found in Table 6.

As is the case with white liquor, black and green liquors also cause general and localized corrosion of carbon steel. Carbon steel corrosion rates of 2.5 mm a year have been recorded in liquor tanks (6). The stainless steels 304L, 316L, S31803 and S32304 have been shown to be resistant to corrosion. In-plant testing resulted in corrosion rates of less than 0.006 mm/year for these grades and, as in the white liquor testing, S32304 proved to be the best of the stainless steel grades (7).

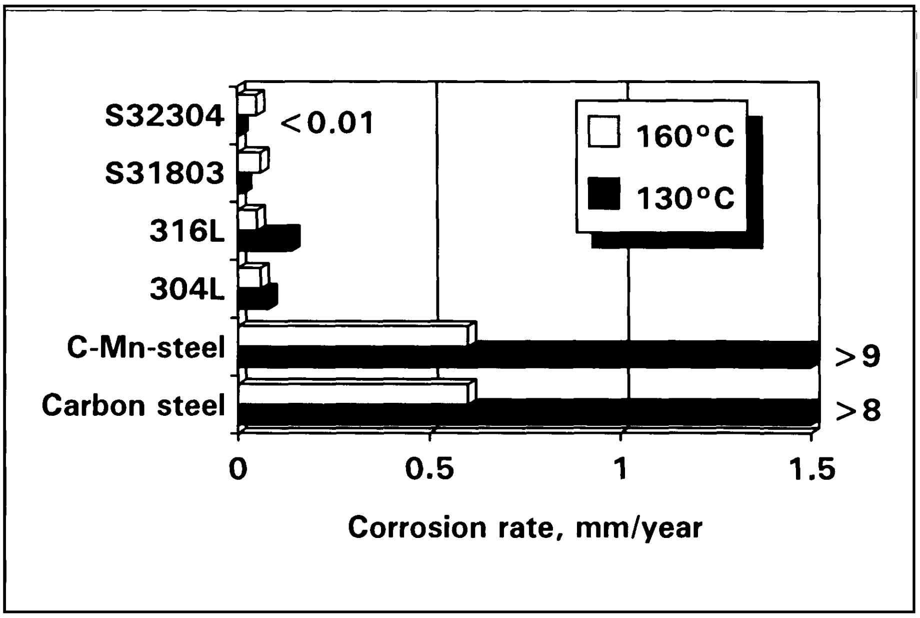

Figure 1.
Corrosion rates in simulated white liquor for modified cooking (5).

Table 6.
Composition of simulated white liquor (5).

NaOH (mole/l)	1.46
Na_2S (mole/1)	0.70
Sulphidity (%)	48.5

Table 7.
Wall thicknesses in millimetres, required according to ASME Section VIII, Division 1, and TKN-87.

Steel grade (ASTM/SS)	Wall thicknesses in mm required according to	
	ASME VIII-1	TKN-87
Carbon Steel[1] (A516:70/1432)	31	30
Austenitic stainless steel (304/2333)	25	28
Clad steel (A516:70/1432 + 3 mm 304/2333)	24	22
Clad steel (A516:70/1432 + 3 mm S31803/2377)	23	20
Duplex stainless steel[2) 3)] (S32304/2327)	21	17
Duplex stainless steel[3)] (S31803/2377)	19	15

1) 8 mm corrosion allowance included.
2) No Swedish pressure vessel approval yet.
3) Stiffeners for vacuum required.

Mechanical Design Aspects

The corrosion test results presented in the previous section show that duplex grades have better corrosion resistance than austenitic grades in both sulphite and sulphate digesters. Duplex grades also offer another advantage; due to the higher strength of duplex steels, extensive wall thickness reductions are possible. This means that less material will be needed for an equivalent design of duplex steel than that of austenitic steel.

Wall thicknesses of a digester have been calculated according to American ASME Section VIII, Division 1, as well as Swedish TKN-87 pressure vessel codes. The resulting wall thicknesses in the lower part of the cylindrical section are shown in Table 7. The design conditions giving these results are 13.5 bar (197 psi), 204°C (400°F), and an inner diameter of 3962mm (156 inches).

The wall thickness required differs not only between the different materials but also depending on the code applied. However, according to both codes, the two duplex alternatives allow for the thinnest walls and thus require the least amount of construction material. Using the Swedish code, the wall thickness required when using S31803 is only 54% of that of a solid 304 wall and 68% of that required for a clad wall. The corresponding figures using the American code are 76% when compared with solid 304 and 79% when compared with clad material.

So far, at least four mills have exploited the advantages of solid S31803 digesters. A total of twelve digesters, two oxygen delignification reactors, and six other pressure vessels made of duplex steel are in service within the pulp industry today, the oldest since 1988 (end of 1994: 28 digesters, 11 reactors, and 12 other pressure vessels).

Table 8.
Materials and costs for a 1 500 m^3 pulp storage tower.

	Duplex stainless steel, S32304				Carbon steel + austenitic stainless steel			
	Grade	Weight tonnes	Cost kSEK	Total kSEK	Grade	Weight tonnes	Cost kSEK	Total kSEK
Material								
Shell	S32304	35.3	670.2		316	22.4	425.0	
					A612	24.6	83.6	
Pre-cutting			24.7				32.9	
Lining, 2 mm					316	5.0	94.2	
Stiffeners	304	3.1	51.3		304	1.1	19.2	
Total, material				746.2				654.9
Fabrication								
Shell			460.0				460.0	
Lining							193.0	
Total, fabrication				460.0				653.0
TOTAL				1206.2				1307.9

Why Use Duplex Grades for Pulp Storage Towers?

The corrosive conditions in a pulp storage tower are not supposed to be as harsh as in a pulp digester. But bleached chemical pulp from a chlorine dioxide stage may carry residual oxidants, and this has caused localized corrosion of storage towers made of 316L. Severe corrosion has also been found in pulp storage towers which have had no connection to any bleach plants, e.g. at mills slushing dried pulp in paper machine white water. Unexpected pitting corrosion of 304L equipment has been found in many white water environments believed to contain low levels of chlorides. One example is a Finnish mill in which the 304L piping systems of a new paper machine started to leak badly after only three months of operation (8). This, and several other failures are unexpected, but not unexplainable. Garner and Newman have shown that 304L steel might suffer pitting in solutions containing thiosulphate even in the absence of chlorides, provided another anion-like sulphate is present (9). Even 316L can show the same type of thiosulphate pitting, but only at higher total ionic concentrations, at higher temperatures, and when chloride is the predominant anion.

Not all pulp storage towers contain corrosive thiosulphate environments or residual chlorine dioxide. Nevertheless, in many cases a stainless steel is required to prevent corrosion. At some mills 304L might be sufficient, whereas at others 316L, S32304 or even higher alloyed grades such as S31803 may be required.

One common way of building pulp storage towers is to use solid stainless steel for the upper part, and carbon steel lined with stainless steel for the lower part. In terms of the material used, the cost of such a tower would indeed be less than if solid austenitic stainless steel had been used to obtain the required strength of the lower part of the tower. But where the costs for the lining of a tower are high, and because the duplex grades are so strong, a tower built of solid duplex steel can be less expensive. Amounts of material and costs for these two alternatives are compared in Table 8. Materials needed derive from linear elastic stress calculations of the tower shells, using a computer program based on the finite element method. Loads caused by weight of the shell, content, insulation, snow, and wind were considered, and the stability of the towers was checked according to Swedish pressure vessel codes.

The result of a comparison such as this is, of course, dependent on the tower size, the prices of the materials included, and labour costs. However, the result clearly shows that a tower of solid duplex steel can be cheaper than a conventional tower of carbon steel and austenitic stainless steel. Using the example of a 1 500 m^3 tower, the cost saving would be 8% if made of solid duplex steel. When a 5 000 m^3 pulp storage tower was built in New Zealand, the saving was reported to be USD 600 000 due to the use of S32304 (10).

Conclusions

- Duplex steels can be used in virtually the same vide range of corrosive environments as austenitic steels. However, the mechanical strength of a duplex grade is considerably higher than that of an austenitic grade with comparable corrosion resistance.
- The duplex grade S31803 performs better than 316L and 317L in the corrosive environment of a sulphite digester.
- Carbon steel suffers various types of corrosion in sulphate batch digesters as well as in continuous ones, whereas stainless steel grades are considerably more resistant.
- Both S32304 and S31803 duplex grades resist sulphate cooking liquor better than 304L and 316L.
- The use of duplex grades as opposed to clad steel, or solid austenitic steel when building digesters and oxygen delignification reactors makes it possible to obtain substantial wall thickness reductions and weight savings.
- Non-pressurized constructions such as pulp storage towers are less expensive when built using solid duplex steel as opposed to a combination of carbon steel and stainless steel, due to the high strength of the duplex grades in combination with the expensive work of lining carbon steel with stainless steel.

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