CORROSION STUDIES AT TECK'S HYDROMETALLURGICAL FACILITY (CESL): IDENTIFICATION OF AN ALLOY SUBSTITUTE FOR TITANIUM IN CERTAIN APPLICATIONS

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Abstract

Titanium has long been the standard material of construction for equipment for low pH, high-chloride service in chemical process industries. However, recent corrosion studies conducted by Teck at their CESL hydrometallurgical copper pilot plant in Richmond, BC, have identified that a super duplex stainless steel may be applicable in some applications where titanium is normally used. This paper will focus on the recent corrosion test results including the rationale for alloy selection, test methodologies and inherent challenges, and comparisons to standard ASTM testing methods.

Introduction

Materials of construction are one of the key design considerations for any process plant where even minor corrosion would be deleterious to operations. Whether corrosion results in the contamination of the process media or a mechanical failure, careful attention to material selection is essential. Such is the case with the CESL hydrometallurgical copper process (CESL Copper Process), which has several unit operations that employ low pH, high-chloride solutions and slurries as the process media. Certain materials, particularly titanium, have a history of high performance in CESL's industrial-, demonstration- and pilot-scale plants. The CESL Copper Process [1] refines copper sulphide concentrates to LME Grade A copper cathodes. Although expensive, titanium, due to its reliability, has been the default material of construction for most equipment in the acid leach area of CESL's copper plant. Equipment routinely constructed from titanium includes the Pressure Oxidation (POX) autoclave, agitator shafts/impellers and pressure piping (e.g. autoclave acid feed and discharge piping).

A testament to titanium's high performance is the POX autoclave for the Usina Hidrometallurgica Carajás (UHC) plant in Brazil—CESL's first semi-commercial copper refinery [2]. This solid, grade 12 titanium vessel operated corrosion-free for nearly two years until the plant was decommissioned. Larger vessels would consist of a steel shell lined with brick or, in the case of Pressure Acid Leaching (PAL) autoclaves, titanium cladding. CESL have actively pursued research on the risks of titanium clad POX autoclaves for commercial-scale applications. During the engineering phase of the UHC project, for example, CESL sponsored an external study [3] on titanium clad ignition. This paper does not consider possible alternatives to titanium for the construction of autoclaves. However, there may be an alloy alternative to titanium for ambient pressure process equipment, as recent corrosion studies at CESL have shown. These studies are the focus of this paper.

A Historical Overview of Corrosion Testing at CESL

Corrosion testing at CESL began early on in the development of the CESL Copper Process when alternatives to titanium were being considered. The purpose of material compatibility testing was to de-risk the use of cheaper, corrosion resistant alloys in a commercial-scale CESL plant. Testing in the early stages was mainly qualitative in nature and did not adhere strictly to any corrosion testing standard. Despite this, these tests did serve to eliminate cheap, easily accessible materials from further consideration. Some of the alloys from these tests were simply placed into storage or displayed as examples of alloys that were clearly not compatible with the process.

Testing standards evolved over time and became more rigorous when the need for material optimization increased. The alloys being tested during this period took the form of small, rectangular plates (coupons) whose masses and dimensions were measured and recorded in order to calculate a general corrosion rate. Consideration was also given to a method of installation of the coupons that would maximize their exposure to the process without interfering with it.

Between 1997 and 2008, five corrosion studies were conducted internally by CESL: one in the copper demonstration plant (~1000 kg Cu/d), two in the copper pilot plant (~35 kg Cu/d), and two in the gold pilot plant (50-100 kg residue/d processed from Cu pilot plant). The process streams in the leach area of the copper plant, where testing was conducted, consist of low pH (1.5-3), high-chloride-bearing (up to 12 g/L) solutions and slurries at elevated temperatures (40-50 °C). In contrast, the gold plant contains high pH (~10), low-chloride-bearing (~0.1 g/L) solutions and slurries at ambient temperature.

The 300 and 400 series stainless steels and the duplex grades that were tested in the gold plant were generally found to be suitable. The alloys tested in the copper plant that were eliminated from further consideration were the nickel-based MONEL® 400 and INCONEL® 600. However, there were several nickel-based alloys that showed no signs of corrosion in the harshest environments of the copper plant outside the POX autoclave. These were HASTELLOY® alloys C-22, C-2000 and C-276; and INCONEL® alloys 617, 625 and 686. The superior corrosion resistance of these alloys over MONEL® 400 and INCONEL® 600 can be attributed to the presence of molybdenum and a higher chromium content. Unfortunately, the costs of these nickel-based alloys are prohibitive, with some comparable to titanium; hence, subsequent corrosion testing involved only those alloys that were considerably less expensive than titanium.

In addition to in-house corrosion testing, four corrosion studies were completed externally by Andrew Garner & Associates Inc. (AG&A) for the CESL Gold Process [4]. External testing on different stainless steels was contracted to AG&A in 2007 in order to identify suitable alloys for the construction of CESL's Gold Demonstration plant. Material optimization for the gold plant continued with a study by AG&A in 2008. Corrosion coupons from several process vessels and tanks in the gold plant were assessed by AG&A in 2011. AG&A also conducted corrosion and redox potential measurements on stainless steels in slurry from the Pressure Cyanidation area of the gold plant at 500 psig oxygen.

Acuren Group Inc. was consulted on the consideration of materials for use in dilute, chloride-laden sulphuric acid solutions. However, no actual testing was performed by Acuren on the alloys that were selected as potentially suitable for such conditions.

Figure 1 below is a material compatibility chart which shows the areas of the copper plant in which the alloys tested are suitable as materials of construction. The chart reflects the results of corrosion tests that were undertaken in the copper plant between 1997 and 2006. As shown in the chart, there are many alloys that are potentially useful.

Legend: Compatible C = Thoroughly tested at CESL conditions
Potential P = Potentially compatible - testwork at CESL conditions to be completed
Incompatible X = Do not use

					Metals																
							Stainless Steels							Nickel Steels							
Temperature (°C)	Chloride (g/L)	Free Acid (g/L)	Other	General Description	Titanium Gr.2	Ti - 45 Nb	316L	CD4MCu (Cast)	Alloy 2205	Alloy-20	254 SMO	654 SMO	904L	Hastelloy C22	Hastelloy C276	Hastelloy C2000	CW2M (Cast)	Inconel 617	Inconel 625	Inconel 686	Incoloy 825
				Solutions & Slurries																	
< 150	3-16	< 80	O_2	Autoclave (inside)	C	C	X	X	X	X	X	X	X	**C**[1]	**C**[1]	**C**[1]	X	X	X	X	X
< 150	3-16	< 80	high velocity O_2	Autoclave (inside)	X	C	X	X	X	X	X	X	X	**C**[1]	**C**[1]	**C**[1]	X	X	X	X	X
< 100	3-16	< 80		AC back end - hot tertiary streams	C	C	X	P	X	P	P	P	X	P	P	C	P	P	X	P	X
< 45	3-16	< 80		Acid feed, evaporator, tertiary loop	C	C	X	P	X	P	P	P	X	P	P	P	P	P	X	P	X
< 80	1-3	< 80		Enhanced Atmospheric Leach	C	C	X	P	P	P	P	P	P	P	P	P	P	P	P	P	P
< 45	1-3	< 80		Primary loop	C	C	X	P	P	P	P	P	P	P	P	P	P	P	P	P	P
< 35	< 0.5	< 80		Atmospheric Leach	C	C	C	P	P	P	P	P	P	C	C	C	P	C	C	C	P
< 45	< 0.03	< 170		Electrolyte	C	C	C	P	P	P	P	P	P	C	C	C	P	C	C	C	P
< 45	0	< 80		Lix 973N (40%)	C	C	C	P	P	P	P	P	P	C	C	C	P	C	C	C	P
< 100	trace	0		Scrubber water	C	C	P	P	P	P	P	P	P	C	C	C	P	C	C	C	P
				Vapours																	
< 100	trace	trace	Sulfur	LP steam, entrained sulphur, Cl	C	C	C	P	P	P	P	P	P	C	C	C	P	P	P	P	P
< 150	trace	mist	Sulfur	Autoclave vent gas / vapour space	C	C	X	P	P	P	P	P	P	X	X	C	P	P	P	P	P
< 40	trace	mist	air	Ventilation systems	C	C	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P

[1] Contact with autoclave solution will corrode these materials over time, but sheathing with PTFE has given them a useful lifetime as oxygen spargers.

Figure 1. Compatibility Chart of Materials Tested in CESL Copper Process

Recent Corrosion Testwork

In 2012, two corrosion studies were undertaken in the copper pilot plant as a further step towards finding optimal materials of construction for a full-scale CESL hydrometallurgical copper refinery. These studies were performed during two important pilot plant campaigns, and utilized three previously untested stainless steel alloys: Lean Duplex 2304 (LDX-2304), Super Duplex ZERON® 100, and Super Duplex 2507 (SAF-2507). Additionally, Standard Duplex 2205 (SAF-2205) and HASTELLOY® C-276 and C-2000—two nickel-chromium-molybdenum alloys—were part of these studies. Prior to this, the only alloys other than titanium found to be suitable for some of the ambient-pressure applications where titanium is traditionally used were HASTELLOY® alloys C-22, C-2000 and C-276; and INCONEL® alloys 617, 625 and 686. Unfortunately, these nickel-based alloys are still too expensive to justify their widespread use in a full-scale CESL plant.

Rationale for Alloy Selection

Interest in testing a variety of duplex and super duplex stainless steels increased as knowledge of this group of alloys improved. LDX-2304 was selected for its relatively low cost and high yield strength. ZERON® 100 and SAF-2507 were selected as they were known to have superior corrosion resistance to the duplex stainless steels, as well as high yield strengths (higher than LDX-2304 and more than twice that of 316 stainless steel). Additionally, compared to the duplex stainless steels and even SAF-2507, ZERON® 100 has superior corrosion resistance to sulphuric and hydrochloric acids and to erosion corrosion and corrosion fatigue. Though more expensive than the duplex stainless steels (e.g. SAF-2205), ZERON® 100 and SAF-2507 were only one-third the cost of titanium at the time of writing.

The remaining alloys—SAF-2205, HASTELLOY® C-276 and C-2000—had already been tested in some capacity; however, the corrosion performance data for these alloys was insufficient

(SAF-2205 had only been tested in the POX acid and thickener feed tanks). Alloys C-276 and C-2000 were selected for testing in the vapour space of the POX autoclave. Though more expensive than titanium, these two alloys were tested because they are less reactive under high oxygen overpressure conditions and therefore may provide a burn path barrier in the event of a titanium fire in the vessel.

Test Methodologies and Challenges

Corrosion coupons were obtained for the aforementioned alloys and varied somewhat in size, shape and finish. The coupons were roughly 25 mm wide and varied in length from 50 to 75 mm, and were from about 5 to 7 mm thick. Due to time constraints, some of the coupons had to be promptly acquired from a local alloy supplier, while others were simply taken from an existing in-house coupon supply. Some of these coupons had been cut from stock plate using plate shears while others had been flame-cut. Thus, the coupons had a rather crude appearance. Suppliers of precision coupons will normally machine and provide a finish to a coupon as per a customer's specifications. A coupon supplier will also clean, pre-weigh and dimension each coupon, if desired. The cleaning, pre-weighing and dimensioning were all done in-house. The coupons were then grouped into sets, and each set destined for a tank or thickener was affixed to the end of a PVC pipe via a titanium threaded rod. The fastening rod passed through a hole in each coupon and was isolated from each coupon via a stepped Teflon washer. On the other side of each coupon was a plain Teflon washer with radial grooves on one side that faced the coupon. The washers also functioned as spacers and provided a minimum 8 mm of separation between the coupons. Ceramic washers were also used for these purposes. Each PVC pipe with its attached coupon set was then installed in the respective tank/thickener.

Each set of coupons was located just above the tank heel or about halfway down the length of a thickener. This was done to ensure the coupons would nearly always be fully immersed in the solution/slurry. Only when the level in a tank was very low (i.e. at the heel) were the coupons partially exposed to air. However, the exposure time was brief in most cases. Care was also taken to ensure the coupons would not come in contact with any instrumentation or heating/cooling elements. The coupons placed in the POX autoclave vapour space were fastened with a titanium bolt to a bracket attached to one of the vessel end flanges (again using isolation washers).

The dimensions of each coupon could not be accurately measured due to the imprecision with which the coupons were fabricated. These dimensions, which include the diameter of the mounting hole, are used to calculate the surface area of the coupon. This in turn is used in the calculation of a general corrosion rate according to the following correlation [5]:

$$R = \frac{KM}{DAT} \tag{1}$$

where

$R =$ Rate of general corrosion (mm/y)
$K =$ Constant $= 87{,}600$ for a corrosion rate expressed in mm/y
$M =$ Mass loss (g)
$D =$ Alloy density (g/cm^3)
$A =$ Surface area of coupon (cm^2)
$T =$ Test duration (h)

While the variables M, D, and T were determined with good accuracy, the surface area was not, owing to the inability to accurately dimension the coupon. Therefore, the rate of general corrosion calculated from Eq. (1) was somewhat inaccurate.

Another challenge lay in cleaning the coupons after removing from the process at the end of the tests. The coupons were cleaned using a 3-4% hydrochloric acid (HCl) solution. Considerable effort was required to remove dirt and scale from the coupons while minimizing exposure to the acid, which is mildly corrosive. This method was not effective in removing the hard scales that were on the surfaces of the C-276 and C-2000 coupons that had been installed in the POX autoclave. Some of this scale was removed using a plastic scraper. The hard scale that covered most of the C-2000 coupon and part of the C-276 coupon precluded a quantitative evaluation of corrosion damage for these alloys, though the uncoated portions were readily inspected for pitting corrosion.

Comparisons to ASTM Corrosion Test Practices

There are some notable procedural differences between the two CESL corrosion studies completed in 2012 and those that adhere strictly to ASTM corrosion test standards (Standards) [5]. The differences concern the way the alloy specimens (coupons) were prepared for testing and the post-test cleaning and weighing methods.

To be truly representative of the component in service, an alloy specimen for corrosion testing must:

1) be identical in composition;
2) be exposed to the same corrosive environment;
3) have the same heat treatment (including that due to welds);
4) have the same plastic strains (due to forming);
5) be subjected to the same service loads; and
6) have the same surface finish.

A rigorous test program should satisfy all these requirements. Requirements 1 through 6 are not explicitly stated in the Standards, but serve as a general guideline for corrosion testing. For the CESL corrosion tests, only Requirements 1 and 2 were wholly satisfied. The coupons were weld-free and were either flame-cut or sheared from stock material and would have met Requirements 3 and 4 depending on the component used in service. Though Requirement 5 was not met, the effect of the difference should be minimal assuming the loading is well within design limits. Surface preparation can have a marked effect on corrosion behavior, which probably makes Requirement 6 the most important when preparing coupons for testing. The coupons had the same finish as the raw stock, which would be used for equipment such as agitator impellers and tanks (the exposed surfaces would not be machined or polished). Hence, the coupons should have satisfied Requirement 6 to a reasonable degree. Unfortunately, the urgency of getting the corrosion tests underway did not allow sufficient time to satisfy more of these requirements. As with previous corrosion testing at CESL, the focus has been to inexpensively acquire large amounts of corrosion performance data (both qualitative and quantitative), which sometimes precludes a more comprehensive approach.

Pre-test cleaning of the coupons was carried out according to the Standards. Contrary to the Standards, no surface abrading was performed (though the coupons were deburred), and they were not stored in a desiccator after cleaning. Also contrary to the Standards was the precision used in measuring the dimensions and mass of the coupons—only two decimal places (instead of 3) were used for dimensioning in millimeters and four (instead of 5) were used for the mass in grams. The precision of these measurements was limited by the instruments used, though the rough and somewhat irregular edges of the coupons did not justify greater dimensioning precision.

Post-test cleaning of the coupons was accomplished with a 3-4% HCl solution and a toothbrush. Specks of process solids that remained after the initial cleaning in fresh water were gently removed with the brush while in the HCl solution. There were also traces of corrosion products on the surface of some coupons, most of which were easily removed with the HCl solution and brush. The Standards outline a multi-step procedure for removing corrosion products that involves several different reagents for each cleaning step; however, this procedure was not applied to the coupons that were tested since the corrosion products had been removed with ease in the HCl solution. The Standards also recommend cleaning a replicate, uncorroded control specimen by the same method used on the test specimen. The control specimen is weighed before and after cleaning to determine the amount of mass loss due to cleaning. However, in view of the fact that many of the coupons had been exposed to a low-pH, high-chloride environment for approximately 2 months during the test and contact with the HCl solution was very brief, a control specimen was not utilized.

Corrosion Test Results

The results from the two corrosion studies conducted in 2012 are summarized in Table I below. The start and end date of each of the two corrosion tests are also indicated. Depending on the test location, the duration of testing for Corrosion Study #1 varied from 912 to 1344 hours while that of Corrosion Study #2 varied from 1680 to 1872 hours. Though the majority of coupons were installed on the same day, a few were installed a week or two later and one coupon set in Corrosion Study #1 (for CCD 2 Thickener) was removed more than two weeks early to conduct maintenance but was never returned.

The technical criteria for selecting an alternative to titanium on the basis of corrosion were as follows:

1) A rule-of-thumb maximum allowable corrosion rate for general corrosion is 0.5 mm/y.
2) The complete absence of surface pitting.
3) The absence of crevice corrosion.

Table I. Results of Corrosion Studies #1 and #2

			Corrosion Study #1 (Feb 20, 2012 - Apr 16, 2012)				**Corrosion Study #2 (May 8, 2012 - Jul 25, 2012)**			
Test Location	**Alloy**	**Relative Alloy Cost ($/$Ti)[1]**	**Process Temp. (°C) Target (Actual)[2]**	**Chloride Tenor (g/L)**	**General Corrosion Rate (mm/y)**	**Visible Corrosion**	**Process Temp. (°C)**	**Chloride Tenor (g/L)**	**General Corrosion Rate (mm/y)**	**Visible Corrosion**
POX Acid Feed Tank	LDX-2304	0.16	40-60 (35.0)	12.0	-[3]	Severe Pitting	30-40	12	N/A	N/A
	SDX-2205	0.18			0.18	None			0.13	Minor Pitting
	ZERON® 100	0.31			0.025	None			0.0017	Minor Crevice
POX Thickener Feed Tank	LDX-2304	0.16	50-60 (19.9)	9.5	0.0093	None	50	12	-[3]	Severe Pitting
	SDX-2205	0.18			0.0007	None			0.076	Minor Pitting & Crevice
	ZERON® 100	0.31			0.0031	None			0.0036	Minor Crevice
PLS Tank	LDX-2304	0.16	40 (45)	8.3	-[3]	Severe Pitting	40	10-12	N/A	N/A
	SDX-2205	0.18			0.031	None			0.13	Minor Pitting & Crevice
	ZERON® 100	0.31			0.0017	None			0.0089	Minor Crevice
Raffinate Tank	LDX-2304	0.16	40 (28)	8.0	0.0005	None	30	10	0.19	Minor Pitting
	SDX-2205	0.18			0[4]	None			0.0013	None
	ZERON® 100	0.31			0.0001	None			0.0014	None
CCD 2 Thickener	LDX-2304	0.16	30-40 (18)	~2	0.0075	None	25	~3	0.053	Minor Pitting
	SDX-2205	0.18			0.0022	None			0.0004	None
	ZERON® 100	0.31			0.0025	None			0.0009	None
POX Thickener	SAF-2507	0.35	50 (28)	9.5	0.0011	None	40	12	0.0006	Minor Crevice
CCD 1 Thickener	SAF-2507	0.35	40-50 (18)	3.6	0.0025	None	25	8	0.0007	Minor Crevice
POX Autoclave Vapour Space	C-276	1.2	150 (150)	-	0.052	None	150	-	0.36	Pitting & Crevice
	C-2000	>1.2			Indeterminate	Inconclusive			N/A	N/A

[1] Cost expressed as a percentage of the cost of titanium. This ratio will vary, depending on the type and size of stock.

[2] The actual temperatures (in parentheses) for the POX Acid Feed Tank and the POX Thickener Feed Tank are averages calculated from logged temperature data. The POX Thickener Feed Tank was cooled (to protect the POX Thickener), resulting in an average temperature much lower than the target. The actual temperatures for the other tanks were manually measured on a one-time basis.

[3] A corrosion rate was not determined since the pitting corrosion damage was so severe.

[4] Calculated corrosion rate was negative, therefore assumed to be zero.

The performance of the alloys in the two studies was variable, with varying degrees of crevice, pitting and general corrosion. Although a general corrosion rate was calculated, its usefulness as a measure of corrosion is questionable for two reasons: 1) there was considerable uncertainty in the measured coupon dimensions as explained above; and 2) pitting corrosion could have resulted in enough mass loss to affect the calculated rate. Also, the alloys which had no visible corrosion would need to be tested for a longer period to obtain an accurate rate of general corrosion. Pitting corrosion constitutes a failure, no matter how slight, and was evident on some LDX-2304 and SAF-2205 coupons, as well as the C-276 coupon in Corrosion Study #2. Surface pitting tended to be confined to a small area of the alloy, with sometimes only one or two pits present. Pitting corrosion was also observed on the edge of some of the LDX-2304 and SAF-2205 coupons that had been flame-cut. The heat generated from the cutting operation may have impaired the corrosion resistance in the heat-affected zone. One of the LDX-2304 coupons from Corrosion Study #1 (see Table I) had pitting corrosion so pervasive that the coupon, which had retained its shape and finish, became soft to the touch and nearly fell apart upon handling. Crevice corrosion was observed on some of the alloys from Corrosion Study #2 (see Table I) and was quite severe on the C-276 alloy from that study. This corrosion occurred underneath the coupon isolation washers, which had radial grooves intended to provide sites for crevice corrosion. Alloy ZERON® 100 had minimal crevice corrosion from Corrosion Study #2 and, overall, outperformed all other alloys except SAF-2507.

The relative resistance of a stainless steel to pitting corrosion in a chloride-containing environment can be quantified by the Pitting Resistance Equivalent Number (PREN). It is calculated as:

$$\text{PREN} = \%\text{Cr} + 3.3(\%\text{Mo}) + 16(\%\text{N}) \tag{2}$$

In general, the higher the PREN value, the greater the resistance of a stainless steel to pitting corrosion. PREN values for common stainless steels, including those for three of the four duplex grades that were tested, are shown on the right side of Table II. The three columns on the left side of the table contain the different alloy designations. The PREN value for ZERON® 100 is known to be >40.

Table II. PREN Values for Stainless Steels [6]

EN	AISI	UNS	Cr	Mo	Ni	N	PREN
Ferritic Grades							
1.4512	409	S40900	11.5	-	-	-	**11.5**
1.4016	430	S43000	16.5	-	-	-	**16.5**
1.4113	434	S43400	16.5	1	-	-	**19.8**
1.4526	436	S43600	17.5	1.25	-	-	**21.6**
1.4521	444	S44400	17.7	2.1	-	-	**24.6**
-	-	S44600	27	3.7	2	-	**39.2**
Austenitic Grades							
1.4301	304	S30400	18.1		8.3	-	**18.1**
1.4401	316	S31600	17.2	2.1	10.2	-	**24.1**
1.4438	317L	S31703	18.2	3.1	13.7	-	**28.4**
1.4439	317LMN	S31726	17.8	4.1	12.7	0.14	**33.6**
1.4539	904L	N08904	20	4.3	25	-	**34.2**
-	(6%Mo)	-	20	6.1	18-24	0.2	**43.3**
Duplex Grades							
1.4362	2304	S32304	23	0.3	4.8	0.1	**25.6**
1.4462	2205	S32205	22	3.1	5.7	0.17	**35.0**
1.4410	2507	S32750	25	4	7	0.27	**42.5**

A comparison between the results of the two studies reveals a striking difference in alloy performance. Most of the alloys from Corrosion Study #1 performed extremely well whereas most of these same alloys in Corrosion Study #2 had at least some visible corrosion. Table III presents the chemical assays for the solutions where the greatest disparities in alloy performance between the two corrosion studies occurred. Though corrosion was also very different in the POX Thickener Feed Tank between the two corrosion studies, these differences can be attributed to the large difference in thickener temperature, which was much lower in Corrosion Study #1 (Table I).

Table III: Test Solution Assays

Test Solution	**Cl** g/L	**FA** g/L	**Cu** g/L	**Fe** mg/L	**Al** mg/L	**Na** mg/L	**Mg** mg/L	**As** mg/L	**Ni** mg/L	**Zn** mg/L
Corrosion Study #1 Acid Feed	10.7	61.6	12.3	2495	1775	2167	1802	3	17	1215
Corrosion Study #1 PLS	8.9	9.0	43.7	2609	1889	2158	1856	2	695	1201
Corrosion Study #1 Raffinate	8.0	59.0	11.7	2560	1797	2831	1854	1	681	1179
Corrosion Study #2 Acid Feed	12.5	24.3	13.5	6982	229	76	712	988	50	7323
Corrosion Study #2 PLS	10.3	11.9	28.2	8688	187	57	622	1444	42	7041
Corrosion Study #2 Raffinate	10.3	34.8	11.5	8627	188	58	620	1421	43	6989

Marked differences can be noted between the solutions used in the two studies, specifically in the concentration of free acid and iron. Concentrations of zinc, arsenic, nickel, sodium, aluminum, and, to a lesser extent, magnesium also vary between the two studies. Difficulty is encountered in gleaning any clear cause for the variation in corrosion performance of the alloys tested. Though the concentration of iron, zinc and other elements varied between the two studies, the variation within each of the individual studies was minimal (with the exception of acid concentration). This, combined with the pronounced difference in each study between the coupons installed in the PLS Tank (significant corrosion) and those installed in the Raffinate Tank (relatively low rates of corrosion), suggests that the corrosion behavior is being influenced by something other than solution chemistry. The significant difference in the lengths of the two test periods might have had an impact on the corrosion levels in Corrosion Study #2, which was about 30% longer than Corrosion Study #1. However, it is doubtful whether this difference in time would have caused such variation in corrosion. Slight differences in composition between two samples of the same alloy can sometimes result in different corrosion resistances. However, all coupons of a given alloy type that were used in both studies were obtained from the same stock material, and therefore all would have had equal composition, heat treatment and corrosion resistance. Further study is required to identify potential causes in this variation in performance.

Future Testing of Alloys and Coatings

Future Alloy Testing

Welded coupons of ZERON® 100 and SAF-2507 will be tested in the copper pilot plant during an upcoming campaign. These will be more representative of in-service components. Another super duplex stainless steel recently selected for corrosion testing during this campaign is FERRALIUM® 255. It is considerably cheaper than other super duplex alloys and has good corrosion properties. All of these coupons will be obtained from a corrosion coupon supplier in order to better assess the test results. If the results of these tests are favourable, an actual piece of equipment may be constructed from one of these alloys and tested in the plant. For safety reasons, an agitator shaft and impeller would be the likely choice. Another option would be to return the coupons to the plant and perform a long-term corrosion test (>1 year). The results from such a test should give us greater confidence as to the compatibility of the alloys with the process.

Testing of Coatings

An alternative to corrosion resistant alloys is the use of special coatings applied to the surface of a non-corrosion resistant material, such as carbon steel. Six samples of carbon steel, three of which have been coated with a polyurethane polyurea coating and the others with just a polyurea coating, will be tested in the copper pilot plant during the upcoming campaign. These coatings are spray-applied to the desired thickness. If successful, these coatings could find use on the surfaces of tanks and possibly even agitators, and may one day replace the rubber linings normally used for these applications.

Conclusions

As the results in Table I are preliminary, none of the alloys tested can be recommended as an alternative to titanium. The results also represent the “best scenario” as the coupons used in this work were weld-free. Multiple corrosion trials will be required to establish a strong link between corrosion behavior and the CESL process or show that no such link exists.

ZERON® 100, which is the best alloy among those tested, had minor crevice corrosion and thus technically does not meet the third criterion for selecting an alternative to titanium. However, crevice corrosion can be eliminated with designs that employ welded instead of bolted joints. Thus, ZERON® 100 could potentially be used for certain equipment, such as agitator impellers.

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