AN ENHANCED SUPERAUSTENITIC STAINLESS STEEL OFFERS RESISTANCE TO AGGRESSIVE MEDIA

N.C. Eisinger, J.R. Crum, L.E. Shoemaker
Special Metals Corporation
3200 Riverside Drive
Huntington, WV 25705
USA

ABSTRACT

Marine applications require construction material to resist harsh environments, but yet must be economical to produce and buy. Alloys such as UNS N06686 or UNS N10276 exhibit excellent corrosion resistance, but at a high price. Other alloys, like those in the 6% molybdenum superaustenitic stainless steel (6%Mo SS) family are more economical, but sacrifice much of the corrosion resistance of the higher alloyed materials. Thus, an alloy that could approach the corrosion resistance of UNS N10276, but with a price near the 6%Mo SS alloys would satisfy both of the requirements for marine service. To meet these requirements, a new superaustenitic stainless steel with enhanced corrosion resistance to both general and localized environments has been developed. Corrosion rates for this new alloy and competitive alloys in seawater, in chloride environments, and other applications relevant to marine service are discussed.

Keywords: superaustenitic stainless steel, corrosion, new alloy, mechanical properties, seawater, stress corrosion cracking, nitrogen, sigma phase, pitting, crevice corrosion

INTRODUCTION

Many of the new alloys invented or commercialized recently share a common theme. By increasing the alloying elements, various corrosion or mechanical properties will be improved. Many of these inventions, however, fall short as far as fabricability is concerned. For every elemental addition to an alloy for property improvement, a reaction on the processibility side will occur. For example, many corrosion resistant alloys require a very high (1200 °C or higher) anneal and water quench to avoid secondary phase formation. Others will crack if cold worked. Furthermore, many of the new Ni-Cr-Mo alloys carry a price tag many times that of common stainless steels. To mitigate some of these concerns, a new alloy has been developed that improves on both the corrosion resistance and mechanical properties whilst maintaining similar fabricability and price compared to current 6%Mo SS alloys.

Localized corrosion resistance is of utmost importance for components subjected to seawater service. Crevices, either inherent in a design or unintentional (contaminant build-up or overlapping components), are often the weakest spot of a design[1]. Though some alloys like alloy UNS N06686 are very highly resistant to seawater corrosion[2], they have a price of more than four times that of austenitic stainless steels like 316 or 317. Of course, the corrosion resistance of UNS S31600 type steel in seawater is very poor compared to Ni-Cr-Mo alloys. Super-austenitic stainless steels have tried to fill the void between 300 series stainless steels and Ni-Cr-Mo alloys, but many times their corrosion resistance is not adequate. This relationship is demonstrated in Figure 1. Thus, an alloy with a price between 300 series stainless steels and Ni-Cr-Mo alloys but with corrosion resistance approaching the Ni-Cr-Mo alloys would be a great advancement.

In this report, the alloy development work will be presented, followed by a discussion detailing the crevice corrosion resistance in seawater of the newly developed alloy. Stress corrosion cracking resistance as well as pitting and crevice corrosion data will be presented. Mechanical properties will also be discussed.

ALLOY DEVELOPMENT

As mentioned earlier, the overall goal of the new alloy development was to create an alloy with corrosion properties approaching alloy UNS N10276, but without increasing the sigma solvus temperature above that of UNS N08926. One side effect of alloying additions is the undesired formation of secondary phases during fabrication such as sigma phase. Sigma phase must be avoided during processing as it will lead to severe cracking during hot working. Sigma phase in the final product, either from an improper anneal, poor quench, or extended time at an elevated temperature (580 °C to 980 °C) will severely hinder corrosion resistance and the mechanical properties of an alloy[3]. Sigma phase consists of a molybdenum and chromium rich phase that forms initially along grain boundaries and eventually throughout the microstructure as seen in Figures 2 and 3. In alloys prone to sigma formation, the phase forms during welding, stress relieving, or fabrication. If formed, it is detrimental to both corrosion resistance[4] and mechanical properties and must be solutioned through a subsequent anneal. Thus, the solvus temperature of an alloy should be kept low for ease in processing and especially subsequent annealing. Different alloying elements have widely varying effects on the sigma solvus temperature, but when designing the alloy, care was taken not only to minimize the processing difficulties, but also to maximize the corrosion resistance.

To improve corrosion resistance, the Pitting Resistance Equivalent Number (PREN) was maximized while the secondary phase (σ) solvus temperature was minimized. PREN is simply a number used to compare an alloy's pitting resistance by comparing important alloying elements[5] and is calculated as

$$\text{PREN} = \%\text{Cr} + 3.3\%\text{Mo} + 30\%\text{N} \tag{1}$$

where all percentages are weight percentages. This empirical formula is widely used for stainless steels and allows for a general ranking of alloys, although even alloys with high PREN's can experience localized attack in natural seawater under some circumstances.

A free energy minimization software package was used to predict phase equilibrium and also solvus temperatures. By understanding the effect of individual elements, nitrogen in particular, a significant corrosion resistance gain was realized over UNS N08926, while maintaining a similar σ-solvus temperature for ease in processing. Nitrogen strongly promotes austenite and also helps to suppress the formation of sigma phase. Furthermore, interstitial nitrogen significantly improves the mechanical properties of alloys in this family without harming ductility. Unfortunately its solubility is limited by the nickel content of the alloy. Thus, the maximum amount of soluble nitrogen was added to both improve the PREN and depress the sigma solvus temperature.

Though the benefit of nitrogen is obvious, chromium and molybdenum have mixed results. Both will improve resistance to localized corrosion as seen in Equation 1, but both raise the sigma solvus temperature. Molybdenum, in particular significantly increases the solvus temperature, but as seen in Equation 1, it also significantly increases pitting resistance so a careful balance must be reached. Chromium has a secondary beneficial effect as well. In addition to increasing corrosion resistance to both oxidizing environments and localized attack, it will increase the solubility of nitrogen in the alloy system at hand.

Other elements that increase the amount of nitrogen in the alloy were examined such as vanadium and manganese. Vanadium also had too many negative effects on the final product, such as inclusions, and was thus discarded. Finally, manganese was slightly increased because it has very little effect on the final product but can increase nitrogen solubility. It is important to note that only soluble nitrogen, and not nitrides, will help in corrosion resistance. Nitrides, like most inclusions, can detract from localized corrosion resistance, and thus only interstitial nitrogen should be included when calculating the PREN of a material.

Nickel content, like chromium has positive and negative factors. As nickel content increases, the solubility of interstitial nitrogen decreases but, for a given nitrogen level, an increase in nickel suppresses sigma formation. Nickel is also known to improve resistance to stress corrosion cracking and general corrosion and was thus elevated slightly over the previous composition of UNS N08926.

Once a ballpark alloy composition was determined, ThermoCalc® was used to further optimize the composition. As is seen in Table 1, a variety of initial compositions were examined. These demonstrate the effect of varying nickel, nitrogen, and molybdenum content on predicted sigma solvus temperature. These calculations back up

---

® ThermoCalc is a registered trademark of the Royal Institute, Stockholm, Sweden the initial assumptions that maximizing nickel and nitrogen, while keeping molybdenum low, will minimize the sigma solvus temperature. After deciding on a composition, the chromium was slightly increased to increase the nitrogen solubility. The final composition, 27-7MO, is shown in Table 2 along with other alloys discussed in this paper. This final composition has a PREN of 56 while maintaining a sigma solvus temperature at or below that of UNS N08926. This sigma solvus temperature was verified experimentally on the first commercial heats to be processed.

EXPERIMENTAL

Seawater Crevice Corrosion Testing

Duplicate samples of new nitrogen enhanced 7% Moly superaustenitic stainless steel along with 316L stainless steel, UNS N06625, UNS N10276, and UNS N08367 were cut into 100 mm x 150 mm x as-supplied thickness rectangles and a 12.7-mm hole was drilled in the center of each piece. A standard surface was created on each piece by machining a 63.5-mm diameter circle on both sides of each sample to achieve a roughness of 0.5µm to 1.5 µm. The entire surface of each piece was then brushed with pumice, rinsed with water and then with acetone. As shown in Figure 4, flat polytetrafluoroethylene (PTFE) gaskets were then affixed over the machined area on each side to create crevices. Using a titanium nut and bolt, each gasket assembly was torqued to 8.5 Nm (75 in-lbs). Samples were then immersed in a 397-liter non-metallic test tank shown in Figure 5. The tank was filled with fresh, filtered seawater and was refreshed at a rate of 1.1 L/m. Over the 60-day test period, the temperature remained between 25.2 °C and 30.2 °C with a mean of 29.6 °C. The source seawater hydrology is shown in Table 3. At three intervals during the test period, the corrosion potential of each specimen was measured by point contact with a UNS N06625 shielded probe and high impedance digital voltmeter. After completing the 60-day test, the crevice devices were disassembled and samples were scrubbed with a brush and detergent with a subsequent dip in 30% HNO_3 to remove any staining. Samples were optically examined for any attack and all results were documented. The aforementioned testing was conducted at Laque Center for Corrosion Technology (LCCT), Wrightsville Beach, NC.

Ferric Chloride Testing

To determine relative pitting and crevice corrosion resistance, as compared to other 6%Mo alloys, testing was carried out in accordance with ASTM G 48 methods C and D[6]. All samples were tested in triplicate and were in the mill-annealed condition. Once cut to 25.4 mm x 38.1 mm x thickness, all samples were sanded to a 120-grit finish. A 6-mm hole and countersink (to remove any burr) was drilled in the center of the crevice corrosion samples. Samples were then stenciled, brushed with pumice, and rinsed with acetone. In the case of crevice samples, a ridged PTFE washer was affixed to both sides using UNS N10276 washers, nuts and bolts. The washers were torqued down to 40 in-oz (0.28 Nm) and the assemblies were checked to ensure electrical isolation between the fasteners and the test sample. Samples were then immersed in test tubes containing between 150 to 200 ml of 6% ferric chloride solution stabilized with 1% HCl. Test duration for all tests was 72 hours and temperature was maintained by immersing the test tubes in a water bath. After testing, crevice devices were removed and all samples were scrubbed with pumice and optically examined for attack. If attack occurred on even one of the three samples, the test temperature was lowered by 10 °C and a new set of triplicate samples was tested. If no attack occurred, test temperature was raised by 10 °C and the tests were restarted. The critical pitting temperature (CPT) and critical crevice corrosion temperature (CCT) were then further defined to the nearest 5 °C. Pitting or crevice attack was considered present if the attack was greater than 0.025 mm in depth.

Stress Corrosion Cracking Testing

To examine resistance to stress corrosion cracking, samples were tested in accordance with ASTM G 36[6]. U-bend blanks were cut into 12.7 mm x 101.6 mm x thickness strips and sanded with 120-grit SiC paper. To allow for bolting, 6-mm holes were drilled on either end. The test specimens were then stenciled and bent into U-bends that were held in stress with PTFE-wrapped UNS N06690 bolts and nuts. U-bends were created by bending samples about a 12.7-mm radius until the ends were parallel. Samples were then suspended from a glass rod that was immersed in a solution of boiling 45% $MgCl_2$. Each test piece was inspected at 30x at regular intervals for cracking or failure. After removing samples and rinsing them in distilled water, they were rehung in the $MgCl_2$ solution if failure had yet to occur. Failed specimens were removed from the test environment.

Other Corrosion Tests

For all other corrosion tests, samples were sanded to a 120-grit finish and stenciled. Samples were then brushed with pumice and rinsed with acetone. All weights were then measured to the nearest 0.0001 g. and all dimensions were measured to the nearest 0.001-inch (0.00254 mm). Samples were then immersed in flasks containing a given corrosive environment for 168 hours. For pitting or crevice corrosion tests in other media, the ASTM G 48 procedure was followed with the exception of the time. Crevice tests were run for 24 hours but pitting tests lasted 72 hours as normal. Temperatures were either stabilized via immersion in water baths or at boiling using a hot plate.

RESULTS AND DISCUSSION

Results of Seawater Crevice Corrosion Testing

An alloy that is selected for seawater service must possess resistance to crevices inherent in structure design. To determine the ability of the new alloy to perform in these conditions, it was tested against alloys previously tested in a US Navy program[7]. As seen in Table 4, alloy 27-7MO and UNS N06625 were fully resistant to attack in the test. As expected, the UNS S31603 material exhibited severe attack, both in terms of depth and affected area. The UNS N087367 sample also showed some attack (0.01mm depth) over a large area (80 mm^2) on one sample. Surprisingly, one sample of UNS N10276 exhibited a single shallow (0.02 mm) pit within the crevice area on one specimen. In a previous investigation, UNS N06625 demonstrated slightly less resistance than alloy UNS N10276[6].

The corrosion potential measurements support the data, as seen in Table 5. The alloy 27-7 samples had a very noble corrosion potential, while UNS S31603 specimens displayed an active corrosion potential. In fact, the new alloy's corrosion potential became more noble over the test duration indicating passivation. The corrosion potential of the attacked UNS N08367 sample displayed a significant change from the two unattacked samples. Meanwhile, both the UNS N10276 and N06625 samples displayed relatively constant potentials indicative of little to no attack. The test period for these tests was only 60 days, but previous six-month testing revealed that initiation of crevice attack would occur within the first 30 days[7]. Thus, the test duration should have been long enough to differentiate between the alloys. Figures 6-8 show the as-tested samples of the attacked UNS N08367, UNS N10276, and the resistant alloy 27-7MO.

Results of Ferric Chloride Testing for CCT and CPT

Because pitting attack influences lifetime estimates in material selection, the pitting resistance of materials for seawater service is very important. ASTM G 48 demonstrates a method for ranking the effective pitting resistance of alloys based on the temperature at which pitting or crevice attack first occurs in a standard solution. Thus, to rank the new superaustenitic stainless steel, the tests described in the experimental section were carried out. Results for CCT and CPT tests as well as PREN numbers for tested material are found in Table 6. Because testing was performed pursuant to methods C and D, the CPT's and CCT's for other alloys could be 5- 15 °C lower than previous studies run pursuant to ASTM G 48 methods A or B due to the 1% HCl addition. In the test, the maximum test temperature was 85 °C. Material that did not exhibit either crevice or pitting attack at this temperature has a CCT or CPT listed as >85 °C. Of special importance, note that the new alloy outperforms even UNS N06625 as well as other 6%Moly alloys. The difference now between super austenitic stainless steels and alloys such as UNS N10276 has even decreased as seen in the aforementioned table where neither alloy pitted in the ASTM G 48 environment and the CCT's are very close. Because all material was tested in the mill-annealed condition, no secondary phase, such as sigma, influenced the resistance of the alloys.

Stress Corrosion Cracking in $MgCl_2$

Ni-Cr-Mo alloys are generally resistant to stress corrosion cracking (SCC) in chloride environments due to their high nickel compositions. Austenitic stainless steels, however, suffer severe SCC when exposed to chlorides. Any component that is bent, formed, or otherwise stressed during either installation or service and comes in contact with chloride ions must have acceptable resistance to SCC. As noted previously, the SCC resistance of an alloy is based largely on its nickel content and secondarily on the molybdenum content. Thus, the results from ASTM G 36 in Table 7 are, for the most part, consistent. The failure of the UNS N08031 samples significantly before alloy 27-7MO and UNS N08926 is surprising due to the higher nickel content of UNS N08031. The boiling $MgCl_2$ test is a harsh test that is used mostly to rank the resistance of various alloys. As seen in the testing, the new alloy is equivalent to UNS N08926 but significantly better than UNS N08031 or UNS S34565.

Other Corrosion Testing

For general corrosion resistance, alloy 27-7MO appears to be slightly better than UNS N08926 as seen in Table 8, but for instances where localized corrosion is possible such as CCT or CPT in Green Death, the alloy is far superior due to its design (Table 9). For example, in a chloride rich environment found in some FGD applications, 27-7MO is immune to attack while UNS S31254 and N08926 are both heavily attacked as seen in Table 10. Even UNS N10276 is slightly corroded in this environment of sulfuric acid plus chlorides.

Mechanical Properties and Processing

As mentioned in the alloy development section, nitrogen significantly increases the mechanical properties of stainless steels. The new 27-7MO alloy is no different. As seen in Table 11 and Figures 9 and 10, the mechanical properties of alloy 27-7MO are greatly improved over UNS N08926 and are nearly identical to those of UNS N06625[8]. Like UNS N06625, alloy 27-7MO can also be drawn down to very thin wire without difficulty. Alloy 27-7MO is also readily fabricated by conventional processes. Welding procedures vary slightly from UNS N08926 as AWS ERNiCrMo-3 is no longer an overmatching filler metal. AWS ERNiCrMo-10 or ERNiCrMo-14 filler metals are recommended as overmatching filler metals. For autogenous welding, a post weld heat treatment is recommended for improved pitting resistance.

CONCLUSIONS

1. An optimization of PREN and sigma solvus with the help of commercially available software enabled the creation of a new alloy with optimum structural stability and corrosion resistance
2. This optimum alloy nominally contains 27% Ni, 22% Cr, 7% Mo, 0.35% N, 1% Mn and balance Fe.
3. The sigma solvus calculations were experimentally verified to be close to but slightly higher than actual sigma solvus temperatures and the increased PREN led to marked improvement in localized corrosion resistance in the new alloy.
4. This optimized alloy was very highly resistant to seawater crevice corrosion in testing that showed attack on both alloys UNS N10276 and UNS N08367.
5. The optimized alloy demonstrated better pitting and crevice corrosion resistance than UNS N06625 and other 6%Moly SS alloys in ASTM G 48 conditions. Its resistance approached that of UNS N10276. The alloy outperforms other 6%Moly SS alloys in tested conditions involving FGD environments.
6. The nitrogen addition leads to improved mechanical properties. Actual cold worked properties are nearly identical to UNS N06625 and are far superior to stainless steels such as alloys UNS S31600 or S31700.
7. Special Metals Corporation has commercialized this patented composition as INCOLOY® alloy 27-7MO and the alloy is available in most product forms.

® INCOLOY is a trademark of the Special Metals group of companies

REFERENCES

1. M.G. Fontana and N. D. Greene, Corrosion Engineering, McGraw-Hill Book Company, New York, 1967, p 39-41

2. E.L Hibner and L.E. Shoemaker, “The Advantages of Nickel Alloys for Seawater Service”, Paper No. 629, CORROSION/2000, NACE, Houston, TX

3. J.I. Morley, et al. “Sigma Phase Embrittlement in 25Cr-20Ni Heat Resisting Steels”, Journal of the Iron and Steel Institute, Oct 1952, p. 129-142

4. AL6XN Brochure, Allegheny Ludlum Corporation, Pittsburgh, PA

5. E. Alfonsson and R Qvarfort, “Investigation of the Applicability of Some PRE Expressions for Austenitic Stainless Steels”, International Conference on Electrochemical Methods in Corrosion Research, EMCR ’91, July 1-4, Helsinki, Finland

6. Annual Book of ASTM Standards, 2002 edition, Section 3, Volume 3.02

7. D.M Aylor et al., “Crevice Corrosion “Performance of Candidate Naval Ship Seawater Valve Materials in Quiescent and Flowing Natural Seawater”, Paper No. 329, CORROSION/99, NACE, Houston, TX, April 26-30, 1999

8. W.F. Brown ed., Aerospace Structural Metals Handbook, CINDAS-USAF Handbooks Operation, West Lafayette, IN, 2000 sections 2-1307 and 4-4117

Table 1

Calculated effect of Ni, Mo and N on σ solvus temperature and PREN (from Eq. 1)

Alloy	Ni	Cr	Mo	N	Fe	σ solvus °C	PREN
EXP 1	22	20.5	6	0.2	51.3	1121	46.3
EXP 2	22	20.5	6.5	0.2	50.8	1161	47.95
EXP 3	22	20.5	7	0.2	50.3	1201	49.6
EXP 4	22	20.5	6	0.28	51.22	1073	48.7
EXP 5	22	20.5	6.5	0.28	50.72	1112	50.35
EXP 6	22	20.5	7	0.28	50.22	1151	52
EXP 7	22	20.5	6	0.35	51.15	1004	50.8
EXP 8	22	20.5	6.5	0.35	50.65	1628	52.45
EXP 9	22	20.5	7	0.35	50.15	1110	54.1
EXP 10	25	20.5	6	0.2	48.3	1074	46.3
EXP 11	25	20.5	6.5	0.2	47.8	1114	47.95
EXP 12	25	20.5	7	0.2	47.3	1152	49.6
EXP 13	25	20.5	6	0.28	48.22	1031	48.7
EXP 14	25	20.5	6.5	0.28	47.72	1068	50.35
EXP 15	25	20.5	7	0.28	47.22	1104	52
EXP 16	25	20.5	6	0.35	48.15	994	50.8
EXP 17	25	20.5	6.5	0.35	47.65	1030	52.45
EXP 18	25	20.5	7	0.35	47.15	1066	54.1
EXP 19	27	20.5	6	0.2	46.3	1048	46.3
EXP 20	27	20.5	6.5	0.2	45.8	1085	47.95
EXP 21	27	20.5	7	0.2	45.3	1064	49.6
EXP 22	27	20.5	6	0.28	46.22	1004	48.7
EXP 23	27	20.5	6.5	0.28	45.72	1040	50.35
EXP 24	27	20.5	7	0.28	45.22	1076	52
EXP 25	27	20.5	6	0.35	46.15	969	50.8
EXP 26	27	20.5	6.5	0.35	45.65	1004	52.45
EXP 27	27	20.5	7	0.35	45.15	1039	54.1

Table 1: PREN calculated as Cr + 3.3Mo + 30N.

Table 2

Composition, PREN, and predicted sigma solvus temperature of alloys tested

Alloy	**Ni**	**Cr**	**Mo**	**Fe**	**N**	**Mn**	**other**	**PREN**	**s solvus predicted (°C)**
27-7MO	27	22	7	Bal	0.35	1	0.8% Cu	56	1095
UNS N08926	25	20.5	6.5	Bal	0.20	0.6	0.8% Cu	48	1113
UNS S31254	18	20	6	Bal	0.22	0.4	0.75% Cu	46.4	1150
UNS N08367	24	21	6.5	Bal	0.22	0.35		49	1137
UNS N08031	31	27	6.5	Bal	0.2	1.5	1% Cu	54.4	1257
UNS S34565	17	24	4.5	Bal	0.5	5		53.9	1060
UNS N10276	Bal	16	16	6	0.01	0.4	4% W	67.2	Mu phase
UNS N06625	Bal	22	9	3	0.01	-	3.5% Nb	52	Mu phase
UNS S30400	9	18.5	-	Bal	0.03	1.4		20.4	Not tested
UNS S31603	10	17	2.1	Bal	0.05	1.4		25.4	Not tested

Note that solvus temperatures are accurate in pattern only. Actual solvus temperatures were experimentally found to be about 15-20 degrees higher than predicted

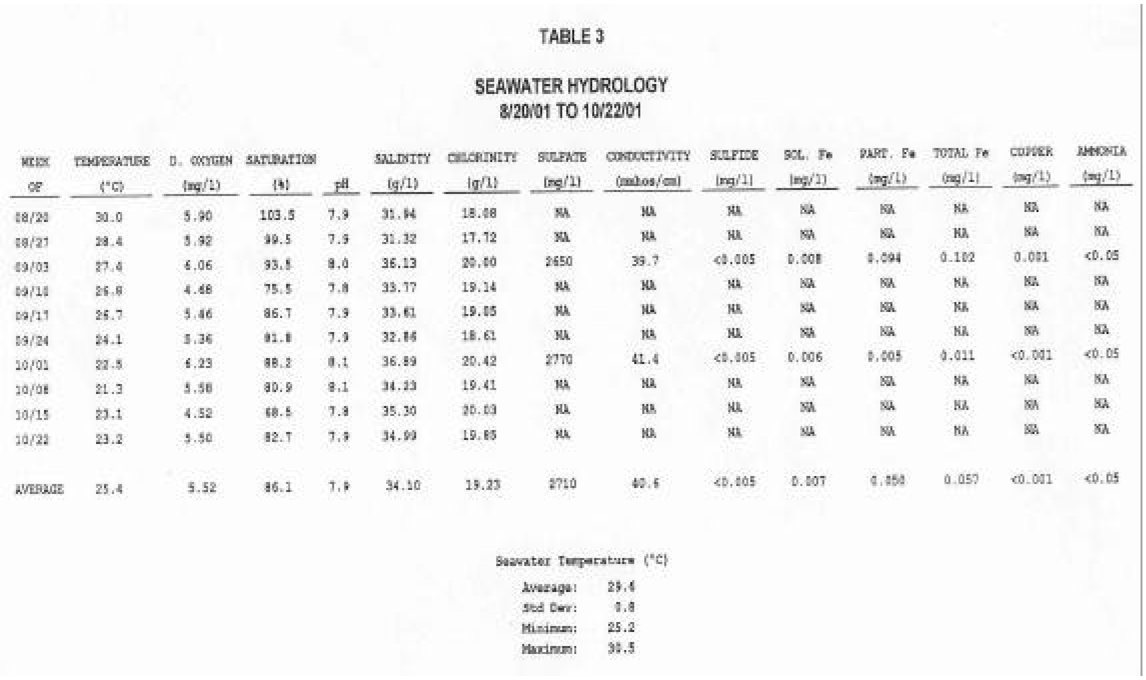


TABLE 3

SEAWATER HYDROLOGY
8/20/01 TO 10/22/01

WEEK OF	TEMPERATURE (°C)	D. OXYGEN (mg/l)	SATURATION (%)	pH	SALINITY (g/l)	CHLORINITY (g/l)	SULFATE (mg/l)	CONDUCTIVITY (mmhos/cm)	SULFIDE (mg/l)	SOL. Fe (mg/l)	PART. Fe (mg/l)	TOTAL Fe (mg/l)	COPPER (mg/l)	AMMONIA (mg/l)
08/20	30.0	5.90	103.5	7.9	31.94	18.08	NA	NA	NA	NA	NA	NA	NA	NA
08/27	28.4	5.92	99.5	7.9	31.32	17.72	NA	NA	NA	NA	NA	NA	NA	NA
09/03	27.4	6.06	93.5	8.0	36.13	20.00	2650	39.7	<0.005	0.008	0.094	0.102	0.001	<0.05
09/10	26.8	4.48	75.5	7.8	33.77	19.14	NA	NA	NA	NA	NA	NA	NA	NA
09/17	26.7	5.46	86.7	7.9	33.61	19.05	NA	NA	NA	NA	NA	NA	NA	NA
09/24	24.1	5.36	81.8	7.9	32.86	18.61	NA	NA	NA	NA	NA	NA	NA	NA
10/01	22.5	6.23	88.2	8.1	36.89	20.42	2770	41.4	<0.005	0.006	0.005	0.011	<0.001	<0.05
10/08	21.3	5.58	80.9	8.1	34.23	19.41	NA	NA	NA	NA	NA	NA	NA	NA
10/15	23.1	4.52	68.5	7.8	35.30	20.03	NA	NA	NA	NA	NA	NA	NA	NA
10/22	23.2	5.50	82.7	7.9	34.99	19.85	NA	NA	NA	NA	NA	NA	NA	NA
AVERAGE	25.4	5.52	86.1	7.9	34.10	19.23	2710	40.6	<0.005	0.007	0.050	0.057	<0.001	<0.05

Seawater Temperature (°C)

Average:	25.4
Std Dev:	0.8
Minimum:	25.2
Maximum:	30.5

Table 4					
60-Day Seawater Crevice Test Results					
Alloy	**Sample**	**Affected Crevice Area (mm^2)**		**Maximum depth (mm)**	
		Stenciled side	**Back Side**	**Stenciled side**	**Back Side**
27-7MO	1	0	0	0	0
	2	0	0	0	0
	3	0	0	0	0
UNS N06625	1	0	0	0	0
	2	0	0	0	0
	3	0	0	0	0
UNS N10276	1	1	0	0.02	0
	2	0	0	0	0
	3	0	0	0	0
UNS S31603	1	1700	0	1.22	0
	2	1745	0	1.01	0
	3	1124	0	2.84	0
UNS N08367	1	0	0	0	0
	2	80	0	0.01	0
	3	0	0	0	0

Table 5

Corrosion Potentials of test pieces vs. Ag/AgCl/Seawater reference

Alloy	Sample	7 days	32 days	60 days
27-7MO	1	0.296	0.316	0.327
	2	0.295	0.311	0.329
	3	0.296	0.314	0.335
UNS N06625	1	0.28	0.295	0.292
	2	0.28	0.279	0.294
	3	0.276	0.296	0.291
UNS N10276	1*	0.277	0.294	0.292
	2	0.275	0.293	0.292
	3	0.273	0.291	0.287
UNS S31603	1*	-0.024	-0.104	-0.13
	2*	0.105	-0.102	-0.026
	3*	0.079	-0.043	-0.056
UNS N08367	1	0.285	0.318	0.34
	2*	0.285	0.311	**0.235**
	3	0.284	0.315	0.328

* denotes sample with crevice attack

TABLE 6: ASTM G 48 Comparison Data

Alloy	**Critical Pitting Temperature per G 48 Method C**	**Crevice Corrosion Temperature per ASTM G 48 Method D**	**PREN**
UNS N08926	70 C	35 C	49
UNS S31254	75 C	35 C	46
UNS N08367	75 C	35 C	47.8
UNS N08031	75 C	45 C	54
UNS S34565	85 C	40 C	52
UNS N06625	>85 C	35 C	52
27-7MO (Commercial)	>85 C	45 C	53
UNS N10276	>85 C	50 C	67.2
27-7MO (Lab heat)	>85 C	55 C	55.5
UNS N06686	>85 C	>85 C	74.1

Table 6: PREN calculated as Cr + 3.3Mo + 30N.

Table 7

A Comparison of alloy 27-7 MO and Various Alloys for Resistance to Stress Corrosion Cracking, Duplicate Samples.

Environment: Boiling 45% Magnesium Chloride.

Alloy	Time to Crack (Hrs.)	Time to Fail (Hrs.)
UNS N08926	<24	<288
UNS N08926	<24	<288
UNS S34565	<6	<24
UNS S34565	<6	<24
UNS N08031	<24	<216
UNS N08031	*	*
27-7MO	<24	<288
27-7MO	<24	<288
UNS S30400	<6	<6
UNS S30400	<6	<6

*Sample was removed from testing after 24 hours due to crack occurring in drilled hole for bolting support

Table 8:

General Corrosion testing, Duration for each test is 168 hours, average of duplicate tests

Temperature	Environment	Corrosion Rate (mpy)	
		27-7MO	**UNS N08926**
65 °C	10 % H_2SO_4	0	0
65 °C	50 % H_2SO_4	24	24
65 °C	98 % H_2SO_4	49	57
Boiling	10 % H_2SO_4	58	59
180°F (82 °C)	10 % HNO_3+ 2 % HCl	0.3	0.4
50 °C	95% H_2SO_4	14	18
50 °C	10% H_2SO_4 + 2% HCl	0	29

Table 9:

Crevice and Pitting Resistance in Green Death

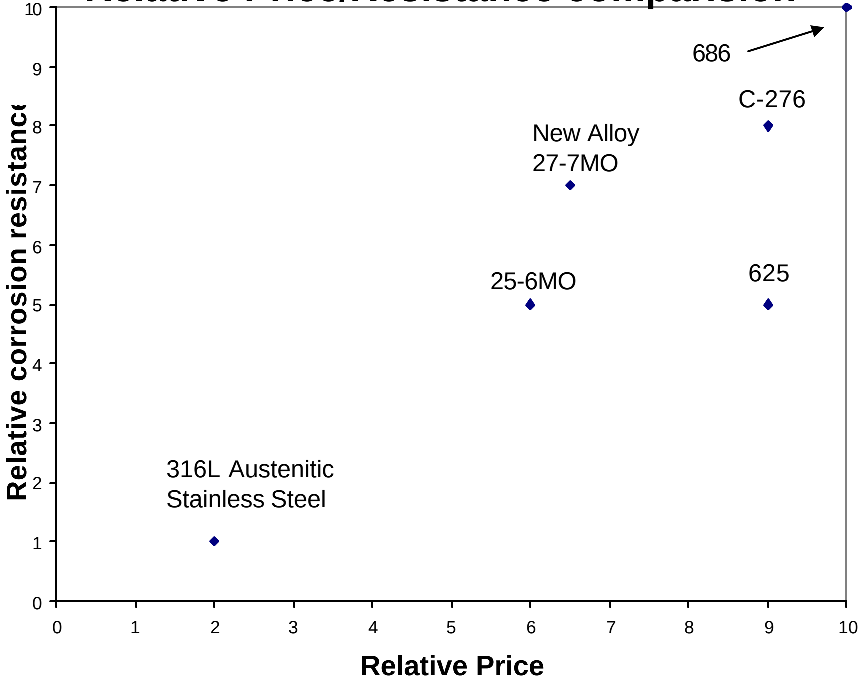
(11.9% H_2SO_4 + 1.3% HCl + 1% $FeCl_3$ + 1% $CuCl_2$)

Alloy	Critical Pitting Temperature in Green Death (°C)	Crevice Corrosion Temperature in Green Death (°C)
	test duration is 72 hours	test duration is 24 hours
UNS N08926	<=60	<50
UNS N08031	<=60	50
UNS N08367	65	50
27-7MO	75	60
UNS N10276	>boiling	90

Table 10			
General corrosion in 10% H_2SO_4 + 10,000 ppm Cl^-			
Temperature = 150 °F (65 °C), Duration = 72 hours, Units = mpy			
Alloy	Trial 1 (mpy)	Trial 2 (mpy)	Average (mpy)
UNS S31254	32	38	35
UNS N08926	30	21	25.5
27-7MO	0	0	0
UNS N10276	0	1	0.5

Table 11			
Mechanical Properties 27-7MO and Other Corrosion Resistant Alloys in the Annealed Condition			
Alloy	**Yield Strength (ksi)**	**UTS (ksi)**	**Elongation (%)**
27-7MO	64	119	50
UNS N08926	48	100	42
UNS S31700	35	85	55
UNS N06625	53	117	70

Figure 1
Relative Price/Resistance comparision



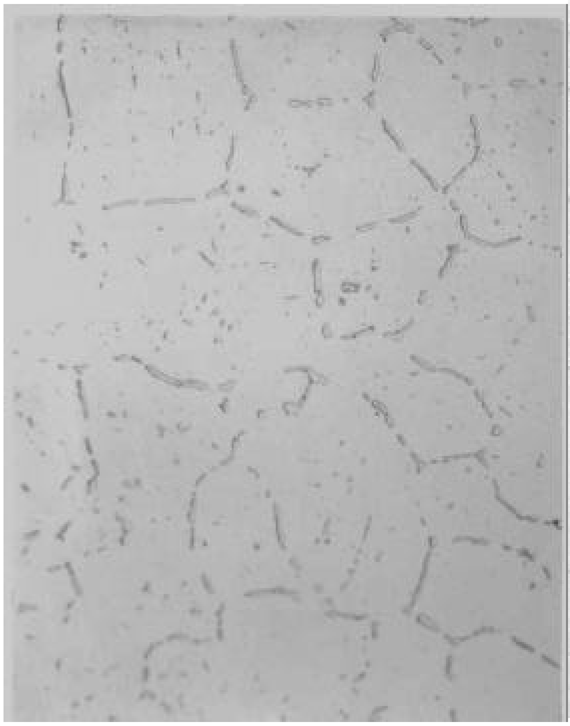


Figure 2: Sigma phase throughout the grain structure of 27-7MO aged 24 hours at 870 °C. Image is 200x and is etched in 2% Bromine.

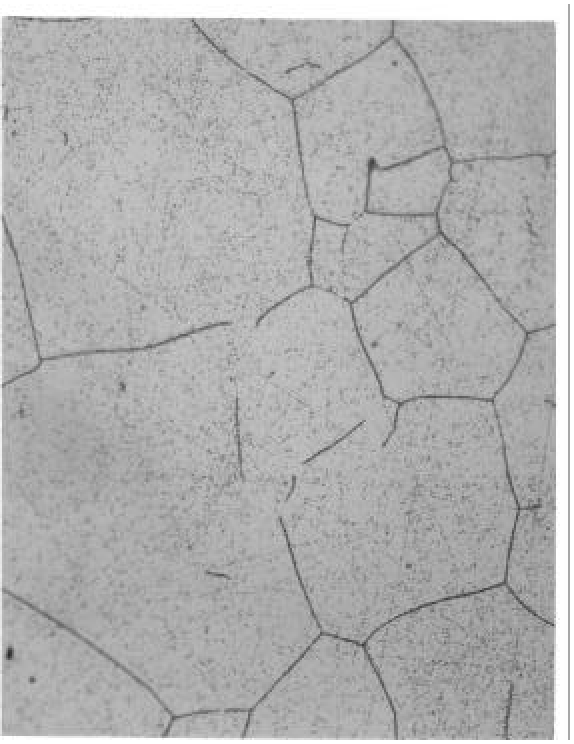


Figure 3: Sigma within the grain boundary and in the grains. This structure was isolated in 27-7MO after 24 hours at 760 °C. Image is 200x and is etched in 2% Bromine.

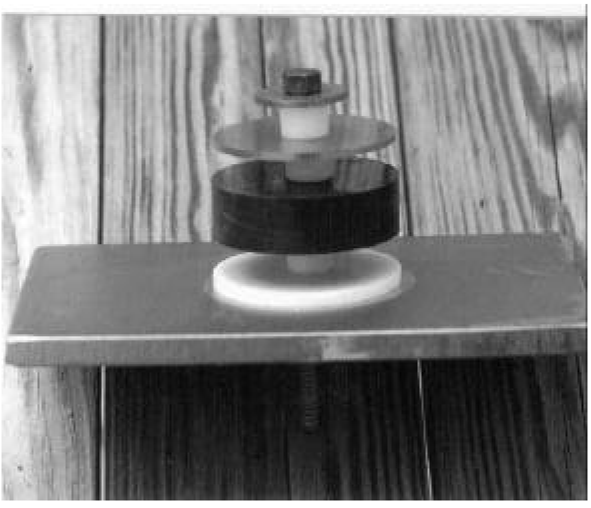


Figure 4: Crevice assembly. Exploded view from top to bottom: Ti fastener, Ti washer, PVC washer, PTFE washer, test specimen. (PTFE sleeves for photo only)

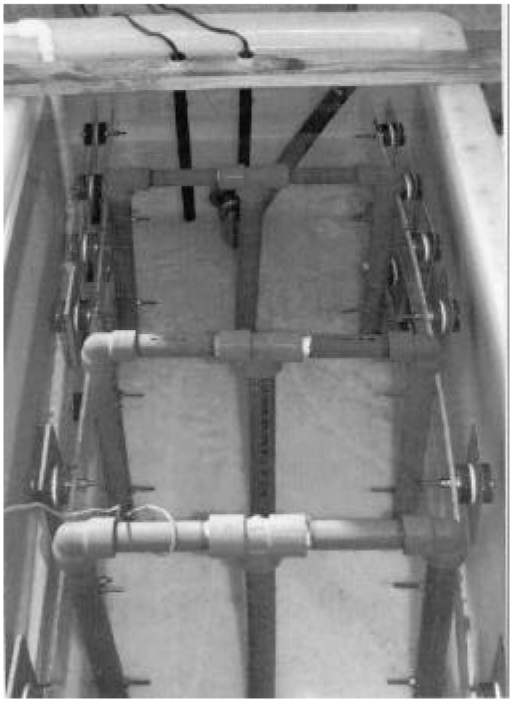


Figure 5: The setup used for crevice corrosion testing in seawater.

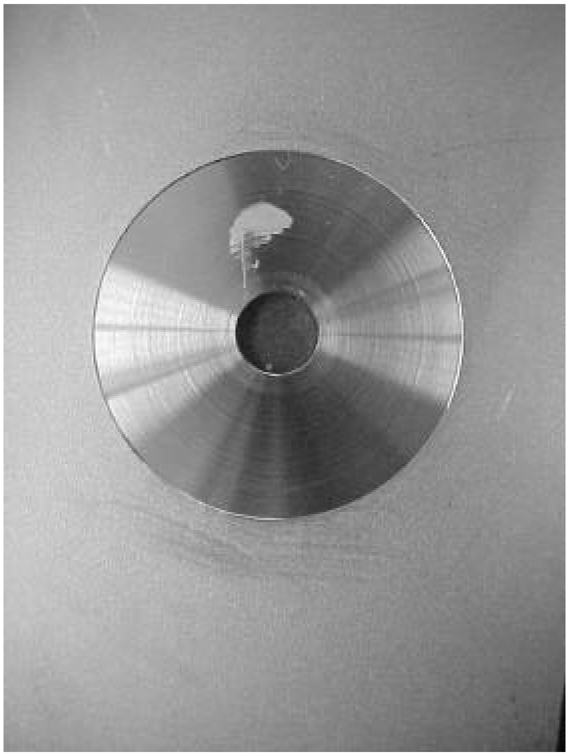


Figure 6: Attack on UNS N08367 after 60-day seawater trial.

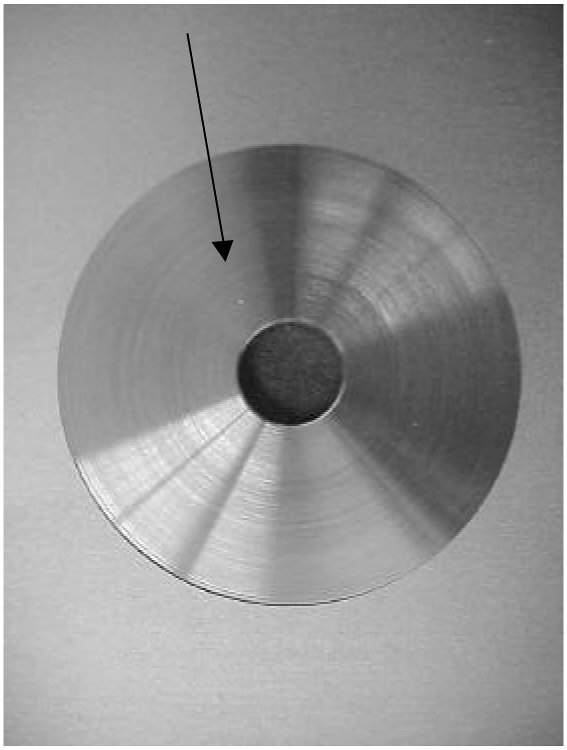


Figure 7: Small amount of attack on UNS N10276 after 60-day seawater trial. (Only one pit)

Figure 8: Unattacked sample of 27-7MO after 60-day exposure to seawater with crevice.

Figure 9
Yield Strength Comparison for Several Corrosion Resistant alloys

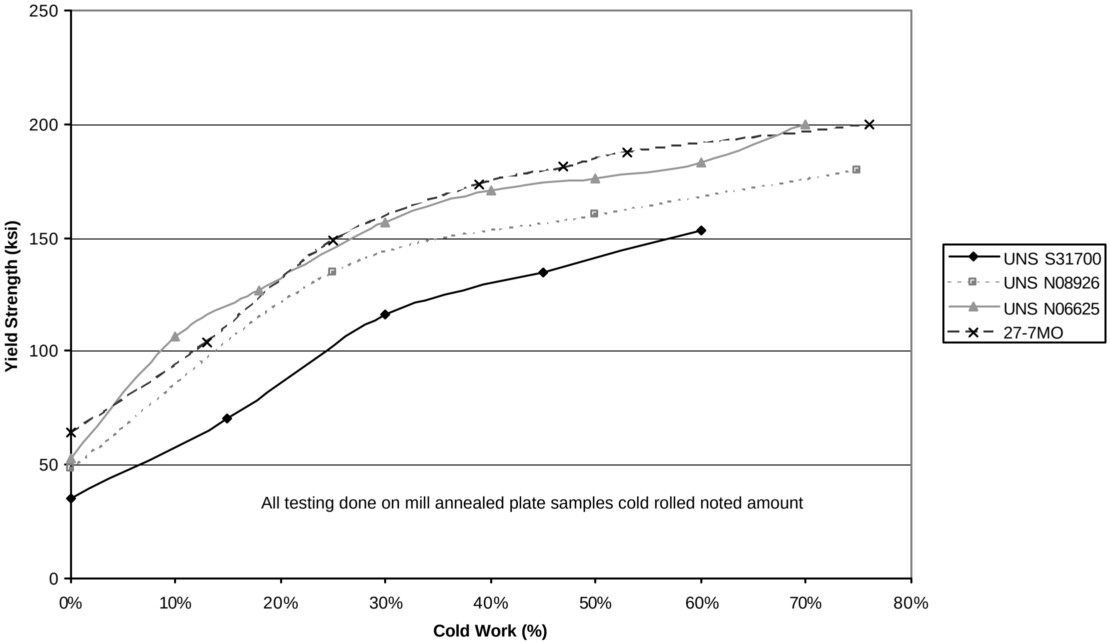


Figure 10
Tensile Strength Comparison for Several Corrosion Resistant Alloys