

654 SMO[®]: Moving the boundaries of stainless steel and challenging Ni-base alloys

UNS S32654 Superaustenitic stainless steel for demanding offshore applications



Abstract

As process conditions in the oil and gas industry become more demanding, the number of potential application areas requiring the use of high-performance superaustenitic stainless steels has increased. This has led to the reintroduction of the UNS S32654 grade (24Cr, 22Ni, 7.3Mo, 3Mn, 0.5N), which has a unique combination of high strength and outstanding resistance to corrosion, making it suitable for use in process streams as well as in seawater handling systems.

This paper presents results for UNS S32654 with regards to localized corrosion in chloride environments. This includes pitting, crevice corrosion and stress corrosion cracking in standardized laboratory tests, and also testing in natural seawater environments. Results are compared with other superaustenitic stainless steel grades such as UNS S31245 and UNS S34565, and to nickel-base alloys such as UNS N10276 and UNS S06625. The results show that UNS S32654 has higher resistance to the different forms of localized corrosion than

the other superaustenitic grades. It is also shown that regarding resistance to crevice corrosion UNS S32654 can be on a par with or better than some nickel-base alloys. UNS S32654 is qualified for use in H₂S-containing environments in oil and gas production within NACE MR 0175/ISO 15156 and details of a number of qualification tests are described. Testing was carried out in accordance with NACE TM 0177 and also in autoclave environments up to 1.4 bar pH₂S and no cracking was observed for UNS S32654.

UNS S32654

Superaustenitic stainless steel for demanding offshore applications

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Introduction

In order to meet the ever-increasing demand for more corrosion resistant materials a number of superaustenitic stainless steel grades have been developed over the years. In the seventies, the 6% molybdenum grade UNS S31254 (254 SMO[®])⁽¹⁾ was introduced [1]. The high molybdenum content together with increased levels of chromium (20%) and nitrogen (0.20%) gave this grade excellent corrosion resistance and improved mechanical properties. Because of its resistance to pitting and crevice corrosion UNS S31254 has been extensively used in the offshore industry for seawater handling. Other alloys with even higher alloying contents were later developed such as UNS S34565. Despite the lower level of molybdenum (4.5%) this grade exhibits increased corrosion resistance because of the higher levels of chromium (24%) and nitrogen (0.45%) [2]. The high nitrogen solubility for UNS S34565 is achieved by alloying with manganese (5.5%).

Even though the above mentioned grades show excellent resistance to pitting and crevice corrosion, there are limitations to the use of these alloys for seawater handling under harsher conditions such as elevated temperature or applications with severe crevice configurations (e.g. plate heat exchangers) [3]. In such applications nickel-base alloys or titanium had to be used. Thus UNS S32654 (654 SMO[®])⁽¹⁾, a second generation superaustenitic stainless steel was developed by further increasing the levels of chromium (24%) and molybdenum (7.3%) which made it possible to reach an even higher nitrogen content (0.5%) [4, 5]. UNS S32654 is still one of the highest alloyed austenitic stainless steel grades produced to date and because of its extremely high corrosion resistance it can replace nickel-base alloys in certain applications.

As UNS S32654 recently has been reintroduced to the market, this study presents results from laboratory standard tests regarding pitting and crevice corrosion, as well as stress corrosion cracking. Previous studies in natural and artificial seawater and laboratory data for sour service environments are also reviewed. The results are compared to those of superaustenitic stainless steels UNS S31254 and UNS S34565, and also nickel-base alloys UNS N06625, UNS N10276 and UNS N06022.

Keywords: Superaustenitic stainless steel, offshore, seawater, hydrogen sulfide, pitting corrosion, crevice corrosion, stress corrosion cracking, sulfide stress cracking.

⁽¹⁾ Tradename

Experimental Procedure

Materials

In Table 1 materials considered in this study are shown with their designations and typical chemical compositions. Minimum mechanical properties according to ASTM are presented in Table 2 [6–8].

Material designations and typical chemical compositions

Table 1

| Designation | | Typical chemical composition (wt%) | | | | | | |
|-------------|-----------|------------------------------------|------|----|----|------|-----|------------|
| UNS | EN/ W.Nr. | C | N | Cr | Ni | Mo | Mn | Others |
| S31254 | 1.4547 | 0.01 | 0.20 | 20 | 18 | 6.1 | — | Cu |
| S34565 | 1.4565 | 0.02 | 0.45 | 24 | 17 | 4.5 | 5.5 | — |
| S32654 | 1.4652 | 0.01 | 0.50 | 24 | 22 | 7.3 | 3.0 | Cu |
| N06625 | 2.4856 | < 0.10 | — | 22 | 62 | 9.0 | — | Nb, Ta, Fe |
| N10276 | 2.4819 | < 0.01 | — | 15 | 57 | 16.0 | — | W, Fe |
| N06022 | 2.4602 | < 0.010 | — | 22 | 56 | 13.0 | — | W, Fe |

Mechanical properties at room temperature, minimum values according to ASTM A 240, B 443 and B 575 [6–8]

Table 2

| UNS | Y.S. | | T.S. | | El. % |
|--------|------|-----|------|-----|-------|
| | ksi | MPa | ksi | MPa | |
| S31254 | 45 | 310 | 100 | 690 | 35 |
| S34565 | 60 | 415 | 115 | 795 | 35 |
| S32654 | 62 | 430 | 109 | 750 | 40 |
| N06625 | 55 | 379 | 110 | 758 | 30 |
| N10276 | 41 | 283 | 100 | 690 | 40 |
| N06022 | 45 | 310 | 100 | 690 | 45 |

Pitting corrosion

The relative resistance to pitting corrosion was evaluated by determining the critical pitting temperature (CPT) according to ASTM G150 [9]. This potentiostatic technique uses a temperature scan and a flushed port (Avesta) cell that eliminates the occurrence of crevice corrosion. From an initial temperature of 0°C, the test solution is heated at 1°C/min while the potential is held at 700 mV versus SCE. The current is monitored and the CPT is defined as the temperature at which the current density exceeds 100 $\mu\text{A}/\text{cm}^2$ for 60 seconds. Pitting on the surface of the specimen is confirmed visually.

The standard test solution according to ASTM G150 is 1M NaCl but the highly alloyed materials investigated in this study do not show pitting at maximum test temperature 90°C. Instead, a 3M NaBr solution was used which lowers the recorded CPT for the tested materials. The surface area tested was 10 cm^2 and 60x60 mm specimens were wet ground 320-grit and left to passivate in air for a minimum of 24 hours before being tested.

The applied potential of 700 mV versus SCE is a typical potential which can be attained when chlorinating water. However, it should be noted that this potential is also close to the transpassive potential for Ni-base alloys so it is particularly important in these cases to verify that pitting has actually occurred.

Crevice corrosion

For determination of the resistance to crevice corrosion the critical crevice temperature (CCT) in acidified ferric chloride was determined using ASTM G48 Methods D and F [10]. Method D is designed for nickel-base alloys and Method F for stainless steels. The tests use 25x50 mm specimens with a hole drilled for the bolt that fastens the crevice washers. Specimens are dry ground 120-grit on all surfaces and left to passivate in air for a minimum of 24 hours. Two MTI-type PTFE crevice washers with 12 slots are applied and fastened with N10276 bolts, nuts and washers with a torque of 0.28 Nm for Method D and 1.58 Nm for Method F. The specimens are immersed in the 6% FeCl₃ + 1% HCl test solution at the desired temperature. The duration of tests is 72 hours for Method D and 24 hours for Method F. At the end of the test period, specimens are inspected and the weight loss determined. Crevice corrosion is considered to be present if the local attack is 0.025 mm or greater. The CCT is defined as the lowest test-temperature that initiates crevice corrosion with 2.5°C increments.

In addition to the standardized ASTM G48 tests, a long term test (500 h) was performed in a 6% FeCl₃ solution at 50°C. The specimens were of the same type as in the ASTM G48 methods described above with an applied torque of 1.58 Nm.

An electrochemical CCT has also been evaluated using a method that is based on the ASTM G150 CPT method. In this case, the flow of distilled water that eliminates crevice corrosion is removed and a flat rubber (EPDM) washer is used to form a crevice against the specimen surface. A wave spring is employed to give a load of 98 N on the crevice assembly. The open surface exposed to the test solution is 1 cm² and the area under the crevice is 3.6 cm². Specimens with dimensions 30x30 mm are wet ground to a coarse surface of 80-grit, in order to provide fine microcrevices between the grinding lines and the washer, and left to passivate in air for at least 24 hours before testing. The test solution is 1M NaCl, the temperature is increased at a rate of 1°C/min from a starting temperature of 0°C and the applied potential is 700 mV versus SCE. The current is monitored and the CCT is defined as the temperature at which the current density exceeds 100 µA for 60 seconds. Crevice corrosion on the surface of the specimen is confirmed visually.

Stress corrosion cracking

One of the most severe conditions for chloride induced stress corrosion cracking (SSC) in stainless steels is when chlorides accumulate on hot surfaces by evaporation. The drop evaporations test (DET) simulates evaporative conditions with a dilute sodium chloride solution and constant load specimens. This test is based on the procedure in MTI-5 Test Method, [11] but the drop frequency is lower. Electropolished tensile specimens with a diameter of 1.8 mm are resistance heated to approximately 300°C and a 0.1M NaCl solution dripped on the surface at a frequency of 6 drops per minute. The specimen temperature is adjusted so that any remaining liquid on the specimen fully evaporates before the next drop reaches the surface. This results in a temperature variation that adds a certain fatigue factor to the test as the specimen strength is effectively varied together with a small variation in length due to thermal expansion – all resulting in a very aggressive test. The test is terminated after 500 hours if complete failure has not occurred by then. The load level is calculated as percent of the measured yield strength at 200°C and the load level is increased until the minimum stress level for failure is established.

Results

Tables 3-7 summarize the results from pitting, crevice and stress corrosion cracking laboratory tests. As shown in Table 3 the CPT for S32654 measured in 3M NaBr under potentiostatic control (700 mV vs SCE) exceeds that measured for all tested nickel-base alloys and two out of three specimens reach the upper temperature limit for the test (90°C). The result for the superaustenitic grade S34565 is almost on a par with the nickel-base grade N06625.

Critical pitting temperature (CPT) under potentiostatic control in 3M NaBr (°C)

Table 3

| UNS | Thickness (mm) | Specimen no. | | | Average |
|--------|----------------|--------------|------|------|---------|
| | | 1 | 2 | 3 | |
| S31254 | 5.0 | 32.2 | 32.7 | — | 32.5 |
| S34565 | 9.2 | 48.9 | 49.7 | 49.3 | 49.3 |
| S32654 | 13.8 | >90 | 85.6 | > 90 | > 88.5 |
| N06625 | 3.0 | 50.8 | 52.9 | 52.9 | 52.2 |
| N10276 | 3.18 | 80.1 | 81.5 | 81.6 | 81.1 |
| N06022 | 3.1 | 74.7 | 61.9 | — | 68.3 |

Critical crevice temperature (CCT) in 6% FeCl₃ + 1%HCl, ASTM G48 Methods D and F

Table 4

| UNS | Thickness (mm) | CCT (°C) | |
|--------|----------------|----------|----------|
| | | Method D | Method F |
| S31254 | 4.0 | 30 | 35.0 |
| | 6.0 | — | 27.5 |
| S34565 | 8.8 | — | 40.0 |
| S32654 | 3.0 | 65 | 57.5 |
| | 2.3 | — | 55.0 |
| N06625 | 3.0 | 40 | 22.5 |
| N10276 | 3.1 | 50 | 40.0 |
| N06022 | 3.1 | 60 | 57.5 |

Table 4 presents the CCT measured with ASTM G48 Methods D and F. For both these test conditions S32654 performs at a similar level to the best of the nickel-base alloys (N06022). The choice of test method clearly has an effect on the ranking of the materials as the superaustenitic grades S31254 and S34565 outperform some of the nickel-base alloys when Method F is used.

Long term crevice corrosion testing in 6% FeCl₃ at 50°C produced results which are presented in Table 5. After 500 hours of exposure S32654 was the only material not showing any signs of crevice attack and with no measurable weight loss. All other materials had extensive crevice attack at all or almost all crevice sites and with crevice depth many times greater than the limit of 0.025 mm. For N06625 the crevice attack had even penetrated the 3.0 mm thick specimen.

Results from crevice corrosion testing in 6% FeCl₃ at 50°C for 500h

Table 5

| UNS | Thickness (mm) | Weight loss (mg) | Corr. rate (g/m ² h) | No. of crevices attacked | Max. crevice depth (mm) |
|--------|----------------|------------------|---------------------------------|--------------------------|-------------------------|
| S31254 | 3.0 | 906.1 | 0.615 | 12 + 12 | 0.711 |
| S32654 | 3.1 | 0 | 0 | 0 + 0 | — |
| N06625 | 3.0 | 1183.5 | 0.810 | 12 + 12 | (*) |
| N10276 | 3.1 | 38.1 | 0.027 | 8 + 12 | 0.184 |
| N06022 | 3.1 | 32.0 | 0.022 | 12 + 12 | 0.299 |

(*) = attack penetrating the specimen

Critical crevice temperature (CCT) under potentiostatic control in 1M NaCl (°C)

Table 6

| UNS | Specimen no. | | | Average |
|--------|--------------|------|------|---------|
| | 1 | 2 | 3 | |
| S31254 | 74.8 | 72.0 | 81.2 | 76.0 |
| S32654 | > 90 | > 90 | > 90 | > 90 |
| N10276 | 54.4 | 51.4 | 54.2 | 53.3 |

Result of DET as number of specimens failed within 500 h out of the total number of tested specimens

Table 7

| UNS | Load level (% of Y.S. at 200°C) | | | |
|--------|---------------------------------|-------|-------|-------|
| | 70% | 80% | 90% | 100% |
| S31254 | 0 (4) | 0 (4) | 1 (4) | 2 (4) |
| S34565 | — | 0 (4) | 2 (5) | 0 (5) |
| S32654 | 0 (2) | 0 (1) | 0 (4) | 0 (2) |

Table 6 shows the electrochemical CCT measured under potentiostatic control in 1M NaCl. Also in this case the CCT is higher for S32654 compared to the only nickel-base alloy tested, N10276.

Drop evaporation test (DET) results are presented as the number of failed specimens out of the total number of tested specimens in Table 7. No cracked S32654 specimens were observed at stress levels up to 100% of the Y.S. at 200°C. However, cracking is observed at 90% for the other superaustenitic grades S31254 and S34565.

Discussion

Field tests in seawater

Results from laboratory pitting and crevice corrosion tests clearly show that S32654 performs on a par with or better than the tested nickel-base alloys N06625, N10276 and N06022 in the standardized corrosion tests. However, these tests are only suitable for ranking of materials and do not say anything about their performance in a particular service environment. In an application the relative performance of the materials could differ from that in the standard tests presented above.

One possible application for S32654 is seawater handling systems at elevated temperatures, and a number of studies in natural and simulated seawater have been carried out over the years.

Feron & Wallen carried out a field test in chlorinated (10 ppm residual chlorine) natural seawater of welded specimens with crevice formers applied with a torque of 40 Nm at a temperature of 45°C for 95 days [12]. The test conditions were very severe as 10 ppm residual chlorine far exceeds the levels found in most seawater systems. The results showed that only S32654 was completely resistant to crevice corrosion as shown in Table 8.

Crevice corrosion in chlorinated (10 ppm Cl₂) seawater at 45°C [12]

Table 8

| UNS | Number of crevice sites | | Max. crevice depth (mm) |
|--------|-------------------------|-------|-------------------------|
| | Crevice corrosion | Total | |
| S31254 | 7 | 8 | 0.98 |
| S32654 | 0 | 8 | — |
| N06625 | 8 | 8 | 0.47 |
| N10276 | 7 | 8 | 0.31 |

Result of PHE and coupon test in chlorinated (2 ppm Cl₂) seawater (North Sea) [13]

Table 9

| Seawater temp. | S31254 | | S32654 | | N06625 | | N10276 | |
|----------------|--------|---------|--------|---------|--------|---------|--------|---------|
| | PHE | Coupons | PHE | Coupons | PHE | Coupons | PHE | Coupons |
| 45°C | 5 (5) | 0 (6) | 0 (5) | 0 (6) | — | 3 (6) | 5 (5) | 3 (6) |
| 50°C | 5(5) | — | 0 (5) | — | — | — | 5 (5) | — |
| 60°C | — | — | 0 (13) | — | — | — | — | — |
| 70°C | — | — | 0 (13) | — | — | — | — | — |

The configuration of a plate heat exchanger (PHE) represents a very severe crevice configuration. Wallén & Wegelius reported on a test in chlorinated sea water (North Sea, salinity 3.3 – 3.6%) where PHEs with nitrile rubber sealing and also test coupons with MTI-type PTFE crevice washer with a torque of 2 Nm were used [13]. The seawater temperature was 45 – 70°C and there was continuous chlorination with 2 ppm residual chlorine. The duration of this test was 3 months. Results from this study are summarized in Table 9 as the number of attacked plates or coupons out of the total number. S32654 showed no signs of crevice corrosion even at the highest temperature of 70°C while S31254 and N10276 both suffered crevice corrosion at 45°C and 50°C. In the coupon test at 45°C both superaustenitic grades passed without crevice attack while at least half of the nickel-base coupons exhibited crevice corrosion. These results also show that the test conditions of the coupons are less severe than the PHE configuration.

Recently, a very similar test has also included Ni-base alloy N06022 with a chlorination level of 1 ppm Cl₂ and where crevice attack was observed at 50°C [14].

In order to investigate the effect of mixed aerobic and anaerobic conditions in seawater a laboratory test reported by Wallén and Alfonsso used specimens with multiple crevice formers (torque 1.58 Nm) that were exposed in 3% NaCl solution at 20°C with hydrogen sulfide continuously bubbled through the solution [15]. The potential was kept at 300 mV versus SCE, a level which could be expected on stainless steels in natural seawater with a biofilm present. The sulfide concentration was 2 000 – 3 000 ppm and the pH 4.0 – 4.8. Crevice corrosion was observed on all specimens of S31254, N06625 and N10276 while S32654 was completely resistant, see table 10.

Environmentally induced cracking

In Figure 1, the results from the drop evaporation testing are compared to data for the standard austenitic stainless steel 316L and the super duplex stainless steel S32750 [16]. Though super duplex stainless steel is considered to have excellent resistance to chloride induced stress corrosion cracking, it is seen that all tested superaustenitic grades have a greater relative stress threshold for cracking.

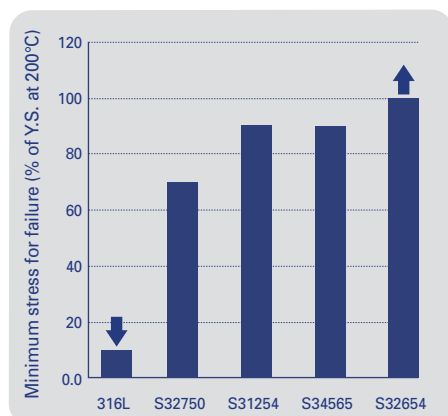
SCC testing have also been performed in artificial seawater (20 000 ppm Cl⁻) under high temperature (232°C) and high pressure (30 bars) with 4-point bend specimens at 100% of Y.S. [16] After test termination at 500 hours no cracking or pitting was detected on S32654 specimens. For S31254 cracking was detected on some specimens and for the

Crevice corrosion in H₂S saturated 3% NaCl at 20°C and 300 mV vs SCE [15]

Table 10

| UNS | Number of crevice sites | | Max. crevice depth (mm) |
|--------|-------------------------|-------|-------------------------|
| | Crevice corrosion | Total | |
| S31254 | 4 | 4 | 0.75 |
| S32654 | 0 | 4 | — |
| N06625 | 4 | 4 | 0.41 |
| N10276 | 4 | 4 | 0.07 |

Fig. 1 DET results as minimum stress for failure.



Ni-Cu alloy N04400 some pitting was detected but no cracking.

As part of the qualification work for NACE MR 0175, [17] the super-austenitic grades S31254 and S32654 were evaluated in laboratory environments simulating sour service conditions in oil and gas production [18]. Testing was carried out in the standard NACE environment (5% NaCl+0.5% CH₃COOH) [19] at 25°C and 90°C and in an autoclave environment at 150°C. The materials were cold worked up to 80% reduction, resulting in hardness up to 47 HRC. A combination of constant load, four point bend and U-bend specimens was used. As shown in Table 11 no cracking was observed for S32654 under any of these test conditions. Also the high strength level achieved from cold working seems to have no adverse effect on the cracking resistance. A comparison with application limits for super duplex stainless steel showed that the superaustenitic stainless steel displays superior performance in sour environments even though cold worked superaustenitics have a higher strength level. As no cracking was observed for S32654, the upper limit for sour service has not yet been established.

Another study used slow strain rate testing (SSRT) of S32654 in 20% NaCl at 177°C with partial pressures of 14 bar H₂S and 14 bar CO₂. The test in this extremely harsh environment gave failure at 5% elongation compared to 65% in nitrogen gas [20].

Summary of testing under sour conditions [18]

Table 11

| UNS | Cold work (%) | Stress (% of Y.S.) | Temp. (°C) | NaCl (%) | pH ₂ S (bar) | pH | pCO ₂ (bar) | Cracking |
|--------|---------------|--------------------|------------|----------|-------------------------|----|------------------------|----------|
| S31254 | 0–80 | 70–90 | 25 | 5 | 1.0 | 3 | – | No |
| | 0 | 100 | 90 | 5 | 1.0 | 3 | – | No |
| | 0 | 90 | 150 | 2 | 1.4 | 5 | 7 | Yes |
| S32654 | 0–80 | 90, 100 | 25 | 5 | 1.0 | 3 | – | No |
| | 0 | 100 | 90 | 5 | 1.0 | 3 | – | No |
| | 0–80 | 90 | 150 | 2 | 1.4 | 5 | 7 | No |

In NACE MR0175/ISO 15156-3, S32654 is included in the category of highly-alloyed austenitic stainless steels with PRE > 40 and the environmental limits are shown in Table 12 [21]. However, these limits are also applicable for austenitic stainless steels with considerable lower PRE value than S32654, e.g. S31254 and S34565, and it may be argued that a new higher class is required for S32654 which has a PRE of 56.

NACE MR0175/ISO 15156-3 environmental limits for highly-alloyed austenitic stainless steels with PRE¹⁾ > 40 [21] used for any equipment or components

Table 12

| Max. temp (°C) | Max pH ₂ S (kPa) | Max. Cl- conc. (mg/l) | pH |
|----------------|-----------------------------|-----------------------|-----|
| 60 | 100 | (2) | (2) |
| 121 | 700 | 5000 | (3) |
| 149 | 310 | 5000 | (3) |
| 171 | 100 | 5000 | (3) |

¹⁾ PRE = %Cr + 3.3 x (%Mo + 0.5x%W) + 16x%N

²⁾ Any combination of chloride concentration and in situ pH occurring in production environments

³⁾ The in situ pH values occurring in productions environments are acceptable

Pitting resistance equivalent

To rank stainless steel according to their resistance to pitting corrosion based on their composition, the Pitting Resistance Equivalent (PRE) is frequently used. It typically takes into account alloying elements that are beneficial for the pitting corrosion resistance such as chromium, molybdenum, tungsten and nitrogen. One common used equation for austenitic and duplex stainless steels is [21]:

$$\text{PRE} = \% \text{Cr} + 3.3 (\% \text{Mo} + 0.5 \times \% \text{W}) + 16 \times \% \text{N} \quad (1)$$

and in Table 13 calculated values for various stainless steels and nickel-base alloys are presented. As the nickel-base alloys N10276 and N06022 have considerable higher PRE than S32654, using equation (1) this ranking is clearly not in agreement with the findings of this study – which indicate that the pitting resistance of S32654 is on a par with or better than the tested nickel-base alloys. Thus, an alternative PRE equation is needed in order to correctly rank superaustenitic stainless steels versus nickel-base alloys. PRE equations proposed in various works for nickel-base alloys include [22 – 24]:

$$\text{PRE} = \% \text{Cr} + 1.5 \times (\% \text{Mo} + \% \text{W} + \% \text{Nb}) + 30 \times \% \text{N} \quad (2)$$

$$\text{PRE} = \% \text{Cr} + 3.3 \times \% \text{Mo} + 11 \times \% \text{N} + 1.5 \times (\% \text{W} + \% \text{Nb}) \quad (3)$$

$$\text{PRE} = \% \text{Cr} + 1.5 \times (\% \text{Mo} + \% \text{W} + \% \text{Nb}) \quad (4)$$

and in Table 13 calculated values using these equations are shown.

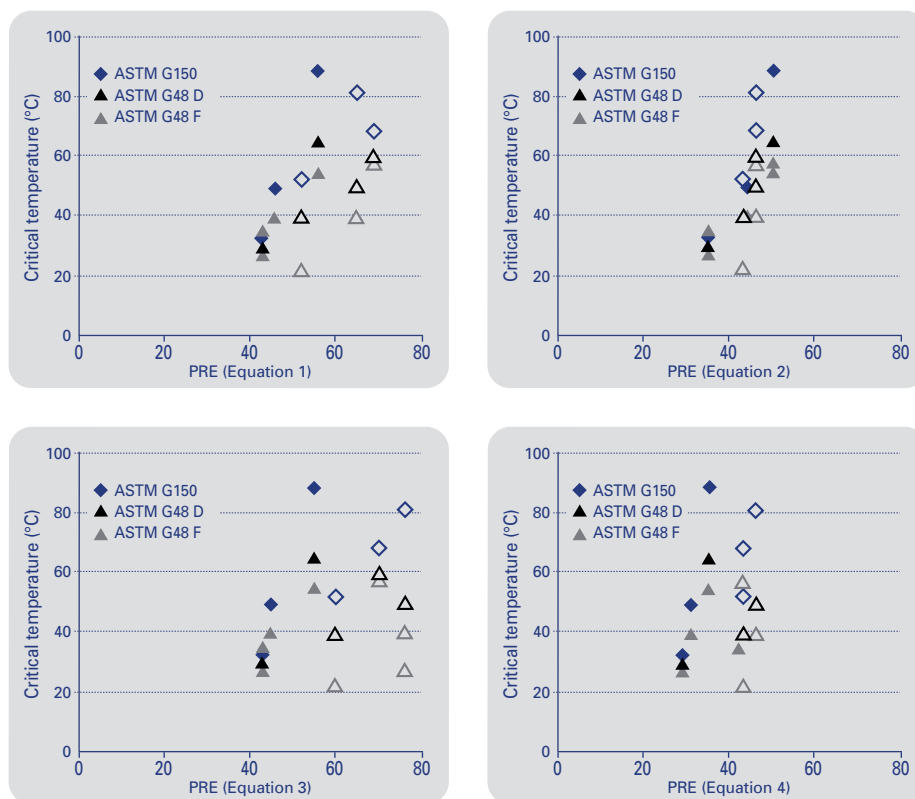
Calculated PRE values using different equations

Table 13

| UNS | Eq. (1) | Eq. (2) | Eq. (3) | Eq. (4) |
|--------|---------|---------|---------|---------|
| S31254 | 43 | 35 | 42 | 29 |
| S34565 | 46 | 44 | 44 | 31 |
| S32654 | 56 | 50 | 54 | 35 |
| N06625 | 52 | 43 | 59 | 43 |
| N10276 | 65 | 46 | 75 | 46 |
| N06022 | 69 | 46 | 69 | 46 |

In Figure 2 the calculated PRE values are plotted against the critical temperatures found in this study (CPT and CCT) and it is found that Equation (2) gives the best correlation between PRE and localized corrosion data across all the grades studied. This emphasizes the importance of including the nitrogen content in the PRE equation when comparing nickel-base alloys and stainless steels as this is an important alloying element for increasing the resistance to localized corrosion of stainless steels.

Fig. 2 PRE using different equations plotted versus measured CPT and CCT. Solid points are for the superaustenitic stainless steels UNS S31254, S34565 and S32654 while open points are for the nickel-base alloys UNS N06625, N10276 and N06022



Applications

Highly alloyed stainless steels such as 6Mo grade S31254 and superduplex grade S32750 has been extensively used for seawater piping on offshore platforms. However, at temperatures exceeding 35°C in combination with chlorination and crevices, corrosion has occurred. S32654 has successfully replaced S31254 in a water cooling outlet where the water temperature periodically could reach 70°C and where severe crevice corrosion was found on S31254 flanges and threaded nozzles [25]. In this case overlay welding with N06625 also suffered corrosion.

Because of the limited supply of titanium, there have in recent years been several studies on replacing titanium in seawater-cooled plate heat exchangers [14, 26]. No satisfactory replacement have been found without restricting conditions such as operating temperature and/or chlorination levels. As the present work shows, S32654 could also be a possibility for this application as its corrosion resistance in seawater is higher than the tested Ni-base alloys and performance of plate heat exchangers has been good. Moreover, for S32654 the high ductility (despite the high strength) is advantageous when forming complex geometries such as those used on plate heat exchangers.

Flowlines in very demanding environments with high contents of chloride, H₂S, and CO₂, and under high pressures often use Ni-base cladding. Using S32654 can provide cost savings due to its leaner composition and better mechanical properties. Secondly, even though duplex stainless steel grades often are used for the so-called carcass in flexible pipes, the higher corrosion resistance (especially in sour environments) and good mechanical properties can make S32654 an alternative in more demanding environments for this application.

Conclusions

This study has shown that superaustenitic stainless steel UNS S32654 has localized corrosion resistance (pitting and crevice) significantly higher than the 6Mo type austenitic stainless steel UNS S31254 or the high-Cr 4.5Mo grade UNS S34565. Its performance is equal to or better than some nickel-base alloys (UNS N06625, UNS N10276 and UNS N06022). This holds true for both standard laboratory tests and tests in simulated and natural seawater and underlines the application potential for this grade in marine and offshore environments.

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