

Corrosion-assisted cracking of duplex stainless steels in suction roll applications

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ABSTRACT: *Corrosion-assisted cracking of suction rolls is a worldwide pulp and paper industry concern despite the great strides in identifying more resistant materials. The authors have examined various tests to assess their use in predicting the susceptibility of suction roll alloys with known service performance. Under conditions of high mean stress and low pH, near-threshold fatigue crack growth testing discriminates among the several materials in approximately the same ranking as their service performance characteristics would have predicted.*

KEYWORDS: *Alloy, corrosion, cracks, stainless steel, test methods, vacuum rolls.*

Failure of suction press rolls in papermaking applications remains a lingering concern for the global pulp and paper industry. Garner (1) and Wooster (2) have documented the statistics of failures of such rolls in North America. These sources indicate that suction roll failures remain a problem despite great strides in the development of more durable alloys for this application.

The mode of failure of suction rolls appears to involve corrosion-assisted cracking. Corrosion fatigue usually links to this to cracking. The cyclic nature of the loading of such rolls and their operation in a moderately

corrosive white water environment would certainly lend credence to this mechanism of failure. The literature only reports a few systematic failure analyses, however. There has also been speculation about the involvement of alternative modes of corrosion-assisted cracking such as SCC. There has been documentation of such involvement only in higher carbon stainless steels that experienced SCC as a result of sensitization during manufacturing processes (3).

Predicting service performance of suction roll alloys based on the results of laboratory tests has not been

very trustworthy. Equipment manufacturers and their paper mill clientele must therefore rely on the results of lengthy tests of prototype rolls in actual service environments to evaluate alternative alloys. This approach is tedious, since rolls must experience several years of operation before an indication of their durability is available. Identification of a laboratory test or tests to predict effectively the resistance of suction rolls to failure by corrosion-assisted cracking would therefore be very desirable. Such testing would decrease the turnaround time for new alloy evaluation and allow screening of more alloys for cracking resistance.

The Institute of Paper Science and Technology has engaged in a long-term program of suction roll alloy testing to identify a test that will provide an accurate assessment of the resistance of suction rolls to cracking in service environments. The approach has involved testing of a variety of alloys with known service performance to attempt to identify a test that will rank alloys accurately according to their actual performance. Studies have included corrosion testing, corrosion fatigue lifetime determination, crack propagation studies, slow strain rate testing, and exposures of autogenously welded samples to aggressive environments. Investigators have previously reported the results of some of these studies (4-8), especially the results of studies of near-threshold fatigue crack growth.

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I. Suction roll alloy composition by weight percentage

Alloy	Cr	Ni	Mo	Cu	C	Fe	Pb	Sn	Zn
<u>Duplex stainless steels:</u>									
A75	26	6.8	—	—	0.03	Bal	—	—	—
A86	26	6.7	—	2.0	0.01	Bal	—	—	—
A378	20	5	2	4.5	0.06	Bal	—	—	—
3RE60	18.5	4.7	2.8	—	0.03	Bal	—	—	—
A171	23	8.3	1.2	—	0.06	Bal	—	—	—
A63	22.5	8.5	1.7	—	0.05	Bal	—	—	—
<u>Bronze:</u>									
1N	—	—	—	Bal	—	—	5.3	4.6	5.0
<u>Martensitic stainless steel:</u>									
CA-15	12.4	0.6	0.5	0.1	0.10	Bal	—	—	—

Bal: Balance

II. Mechanical properties of suction roll alloys

Alloy	YS, MPa	UTS, MPa	RA, %	EL, %
<u>Duplex stainless steels:</u>				
A75	376	763	47.9	30.0
A86	448	797	27.1	22.0
A378	466	733	52.2	39.6
3RE60	549	742	60.8	42.5
A171	426	670	62.5	34.5
A63	396	681	65.7	40.0
<u>Bronze:</u>				
1N	—	270	37.9	41.0
<u>Martensitic stainless steel:</u>				
CA-15	536	679	41.7	18.0

YS: Yield strength
UTS: Ultimate tensile strength
RA: Reduction in area
EL: Elongation

III. Maximum residual stresses measured in welded coupons, MPa

Alloy	As-received	As-welded	Welded and stress-relieved
A75	55	633	76
A378	103	634	103
3RE60	27	537	15
A171	<0	640	<0
A63	241	661	221

A test which determines the threshold stress intensity for corrosion fatigue crack growth under conditions of high mean stress and aggressive environments has pro-

vided the best correlation so far with service performance (5–8). The corrosion resistance of suction roll alloys in simulated white waters provides a poor correlation with dem-

onstrated resistance to corrosion-assisted cracking in service (4). There has long been suspicion of the utility of conventional corrosion fatigue lifetime testing, i.e., alternating stress number of cycles to failure (S–N) curve development, in simulated paper machine white waters.

The most recent Institute of Paper Science and Technology suction roll studies have focused on the following areas:

- Extension of the near-threshold fatigue crack propagation studies to additional commercially available alloys
- S–N testing of duplex stainless steels in very aggressive environments simulating those that might exist beneath deposits and within pits
- Research into the effect of simulated welding on suction rolls and the effect on corrosion-assisted cracking.

This paper reports the progress in each of these areas. As noted above, the overall objective has been to identify a laboratory test that correlates well with service performance of suction rolls in press roll applications.

The alloys examined in these studies consist of a bronze, a cast 13Cr stainless steel, and several duplex stainless steels. Excessive cracking has forced the retirement of some of the latter alloys. In addition, some alloys have had only limited industrial exposure. **Table I** shows the alloy compositions, and **Table II** shows the mechanical properties of the tested alloys. In our testing, we removed the test material from commercial roll sections provided in the heat-treated condition consistent with commercial practice. For the cracking studies, the plane of crack growth in the laboratory coincided with the plane of growth most frequently observed in practice, i.e., the longitudinal circumferential orientation of the crack plane (L–C) orientation (9).

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For the purposes of comparison with laboratory test results, we consider the 1N bronze and CA-15 martensitic stainless steel to have the lowest resistance to cracking in service under aggressive white water conditions followed by duplex alloys A63 and A171. Both of these alloys experienced significant cracking in service. We consider alloys A378 and A75 to be more resistant to cracking, since these alloys are in widespread use with little evidence of cracking. There is currently no record for the resistance to cracking of the A86 duplex stainless steel, since this alloy has only entered service relatively recently. All the alloys are cast except 3RE60 which is a wrought alloy formed and welded into roll configurations. After some early instances of cracking, 3RE60 has generally been resistant to cracking in service.

Near-threshold fatigue testing

Previous results

Earlier studies (5-8) have linked the threshold for fatigue crack propagation with the cracking resistance of several duplex stainless steels in service applications. The threshold is the lowest value of the cyclic stress intensity range, ΔK , at which a sharp crack will continue to propagate. Cyclic stress intensity range is a product of terms involving the mechanical force applied to the cracked specimen, the length of the crack, and a geometric parameter. It has the units, $\text{MPa}\cdot(\text{m})^{1/2}$. Monitoring crack growth with telemicroscopy following carefully staged load reduction sequences determines the threshold value, ΔK_{th} . In a conventional logarithmic plot of crack growth rate versus ΔK , the threshold appears as the value of ΔK below which crack growth does not occur, i.e., the left-most data point.

The threshold for crack growth provides a general ranking of duplex stainless steels that is broadly representative of their performance in the field. In particular, alloys A63

and A171, which have experienced significant cracking in service exhibit thresholds for crack growth that are generally lower than those of the other cast duplex alloys tested. Conversely, A75, which has had extensive use in suction press roll applications without cracking, exhibits higher threshold values. This differentiation among alloys becomes less apparent as the environments become more benign, e.g., as the pH increases or the chloride concentration decreases. It disappears completely for tests conducted in air. The differences among alloys increase with the superimposition of a tensile mean stress during crack growth. The threshold for crack growth relates to critical flaw size for crack propagation under stress conditions which are typical of suction roll alloys (8).

Recent studies

Near-threshold fatigue testing can extend to include two alloys which are not duplex stainless steels and which have exhibited frequent cracking in service applications. If the threshold stress intensity for crack growth is a meaningful test to predict service performance, these alloys should exhibit thresholds that fall below those of the duplex stainless steels. They should at least fall below the more resistant alloys such as A75 and A378.

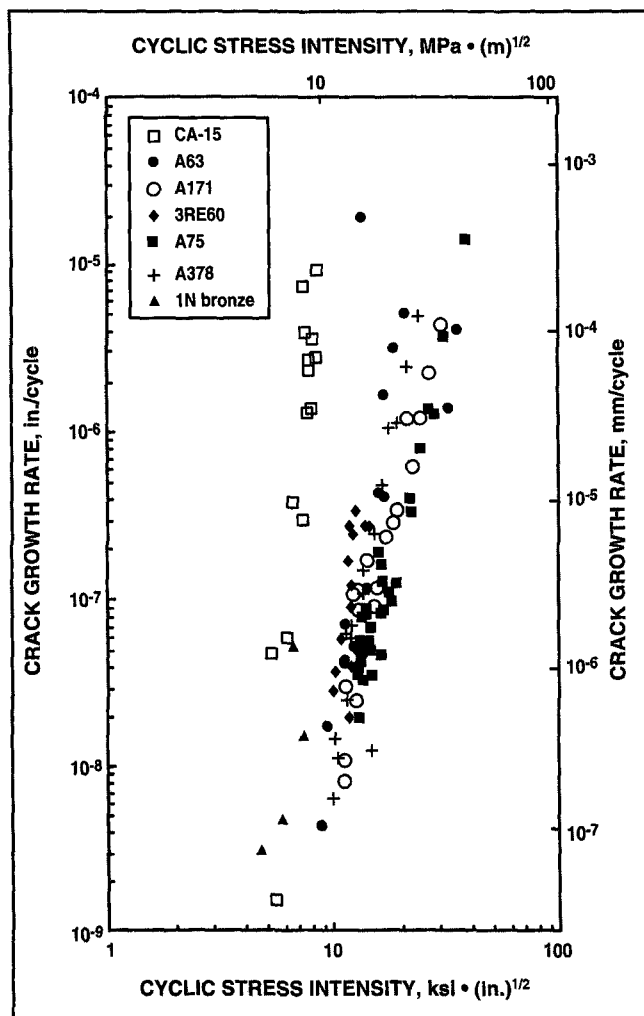
Fatigue crack growth rate measurements of 1N bronze and CA-15 stainless steel determined the threshold for crack growth under conditions previously used for the duplex stainless steels. Tests were in air and in two solutions. One solution contained 1000 ppm Cl⁻ acidified to a pH of 3.5, and the second contained 3000 ppm Cl⁻ and a pH of 1.0. These tests employed the load-shedding procedure previously used to determine the threshold stress intensity for crack growth. Previous reports describe the test method in detail (5-8).

The thresholds for crack growth in the 1N bronze and the CA-15 stainless steel agree with the service experience. They were appreciably below the thresholds observed for the cast duplex stainless steels in air and the materials examined in the two corrosive test solutions. **Figures 1-3** show the results for these tests as plots of the fatigue crack growth rate as a function of cyclic stress intensity range for several suction roll alloys. The figures compare the behavior of 1N bronze and CA-15 with other suction roll alloys. The threshold for crack growth in air for bronze and for CA-15 is approximately half that of the duplex stainless steels. For CA-15, testing in the 1000 ppm Cl⁻ environment induces only a slight reduction in the threshold for crack growth observed in air. This environment affects more significantly some of the duplex stainless steels. In the 3000 ppm Cl⁻ environment, the threshold for CA-15 falls to approximately $3 \text{ MPa}\cdot(\text{m})^{1/2}$, a 50% reduction compared to the threshold in air. A similar percentage loss is also typical of the duplex stainless steels. The cracking threshold for the 1N bronze tested in air is substantially below that of the stainless steels tested in air. The low threshold for bronze tested in air indicates that bronze will be no better than the cast duplex alloys in more aggressive environments.

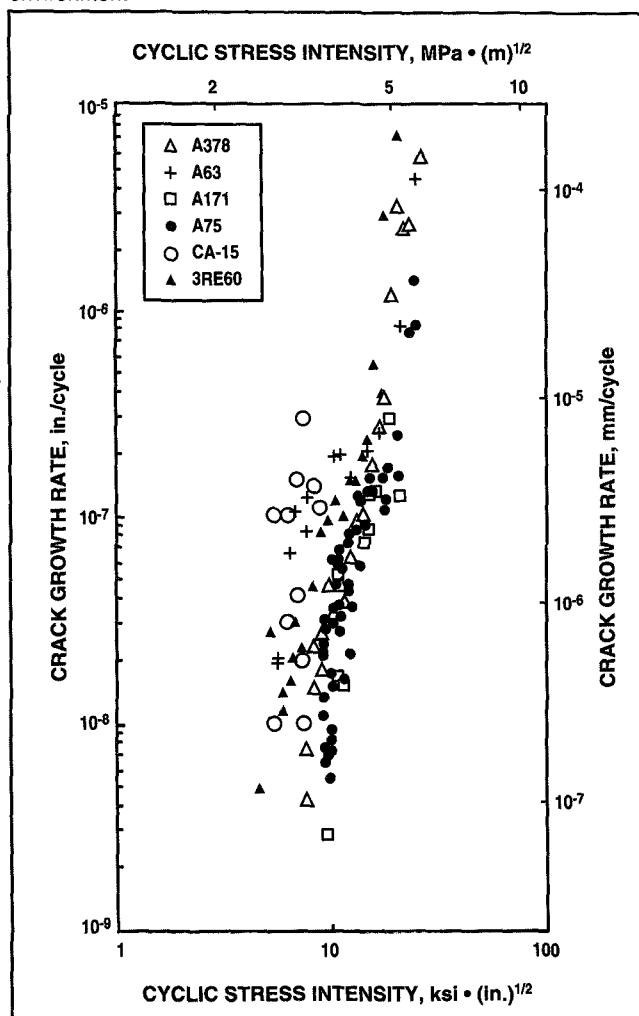
CA-15 and 1N bronze both therefore exhibit ΔK_{th} values that fall below those of the duplex stainless steels that have the greatest resistance to cracking in service. Determination of the threshold values before service exposure of these two materials would have predicted a performance inferior to that of A75. The trend of these results supports the suggestion that the threshold for fatigue crack growth in aggressive environments can rank the relative resistance of cast alloys to corrosion-assisted cracking in service.

The best validation of a predictive test is to use it to forecast the perfor-

1. Fatigue crack growth rate in air



2. Fatigue crack growth rate in a pH 3.5 and 1000 ppm chloride-environment



mance of a new material for which there is no actual service record. As the reliability of the material becomes apparent, the validity of the prediction is evident. This either validates or invalidates the predictive method. To test the validity of the threshold stress intensity for crack growth as a predictor of service performance, we determined the threshold stress intensity for a new duplex stainless steel, A86. This new alloy has a composition similar to that of A75 with 2% copper added for corrosion resistance. Although this has had successful use as a suction roll alloy, the service period is still too short to establish fully the resistance of the alloy in service applications. It is possible to predict eventual per-

formance based on the results of laboratory tests to determine the ΔK_{th} value in a standard test environment.

Figure 4 shows that the threshold stress intensity for crack growth in A86 is somewhat better than that for A75 in the 1000 ppm Cl⁻ environment. These results are consistent with the results of similar tests on A75 and A86 in a thiosulfate containing solution (10). These tests suggest that the cracking resistance of A86 in service applications should be somewhat better than that of A75. Consequently, the threshold stress intensity results available to date predict that A86 will share the A75 record of excellent performance in service. Time will tell whether this

prediction based on measurements of the threshold stress intensity is accurate.

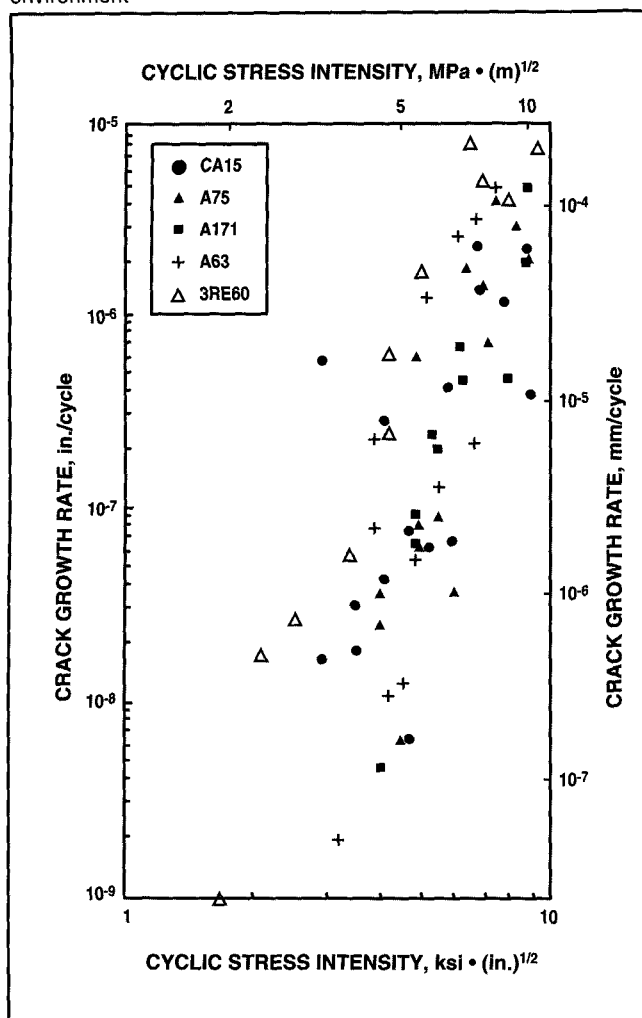
Corrosion fatigue lifetime testing

Previous work

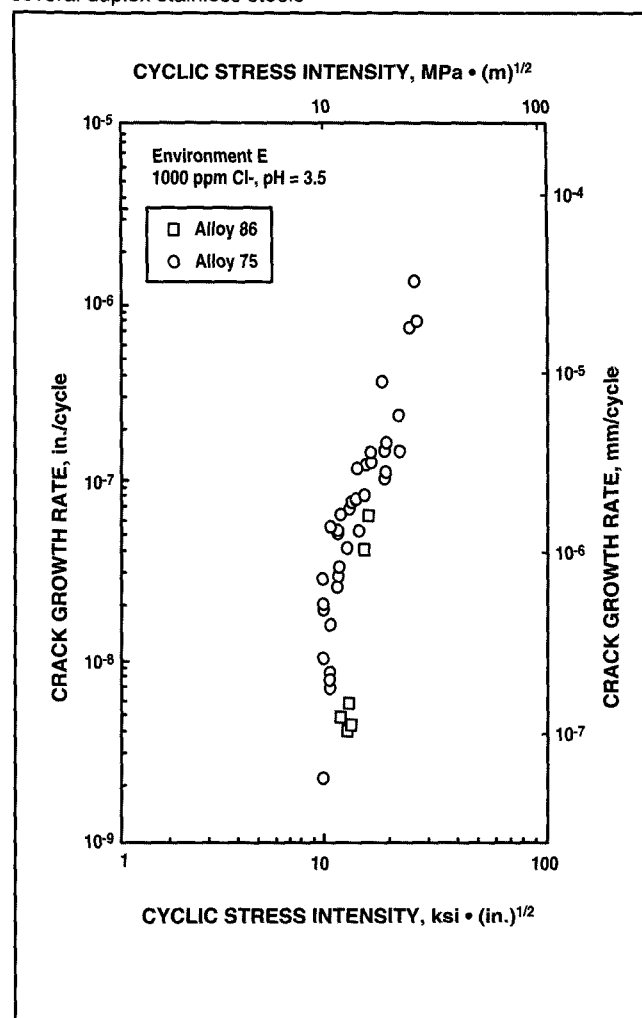
Several authors have found that the S-N behavior at long lifetimes is a relatively poor predictor of the resistance of suction roll alloys to corrosion-assisted cracking in service (4). In most of these studies, the test environments have been fairly benign simulations of paper machine white water. Such environments may not represent the severity of the environments present at the site of crack initiation. This would be espe-

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3. Fatigue crack growth rate in a pH 1.0 and 3000 ppm chloride-environment



4. A comparison of near-threshold fatigue crack growth rates in several duplex stainless steels



cially true if cracks start beneath deposits or at the bottom of pits. In these isolated locations, the separation of anodic and cathodic processes together with the hydrolysis of transition metal ions leads to an acidification of the local electrolyte. There is also an increase in the concentration of anions such as Cl^- and $\text{S}_2\text{O}_3^{2-}$ typically present in white water. Under such conditions, crack initiation may occur under concentrated salt solutions with pH values as low as 1.5.

S-N tests in concentrated solutions

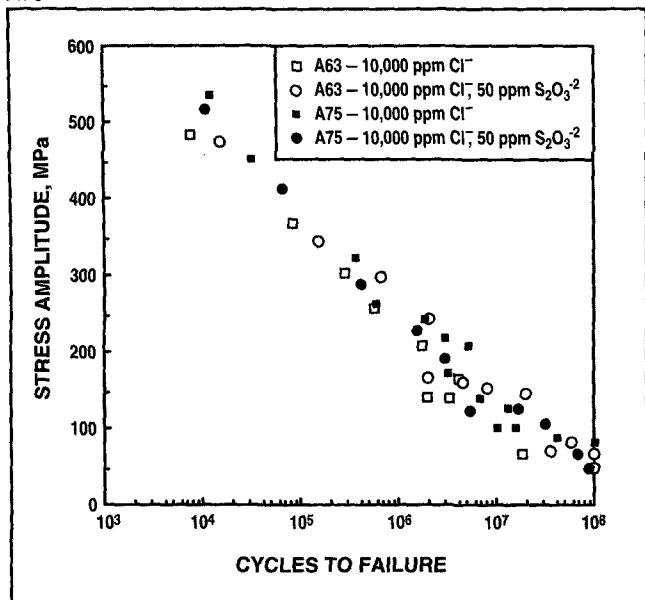
To determine whether the S-N test would better predict service performance if the tests simulated this ag-

gressive localized environment, we performed fatigue tests in test solutions with high levels of chloride and a low pH. We conducted screening tests on two duplex alloys that either have exhibited severe cracking in service (A63) or have been virtually immune from such cracking (A75).

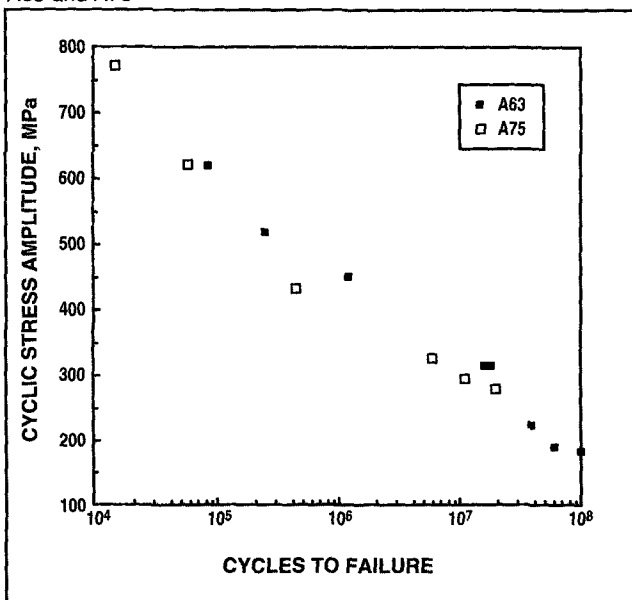
Most of these tests were rotating bending tests conducted using the standard R. R. Moore fatigue testing apparatus, although there were some alternating bending tests to examine the effects of a hole drilled in the test specimen as a stress concentrator. Since lifetimes of 10^8 cycles or greater were desirable, we conducted R. R. Moore tests at a cyclic frequency of 50 Hz. This is several times the rotational fre-

quency of operating suction rolls. The R. R. Moore test specimen had a gauge diameter of 6.4 mm. The alternating bending test specimen was a flat plate 3.2 mm x 6.4 mm containing a 2.4-mm hole drilled approximately 10 mm from the grip. Test solutions flowed over the gauge section of the R. R. Moore test specimens. The alternating bending tests used a wick placed in the hole of the specimen to transfer the test solutions to the surface. Definition of the failure of the R. R. Moore specimens was the complete fracture of the specimen. Definition of the failure of alternating bending specimens was the onset of visible cracking, since the stress conditions are indefinable once cracking begins.

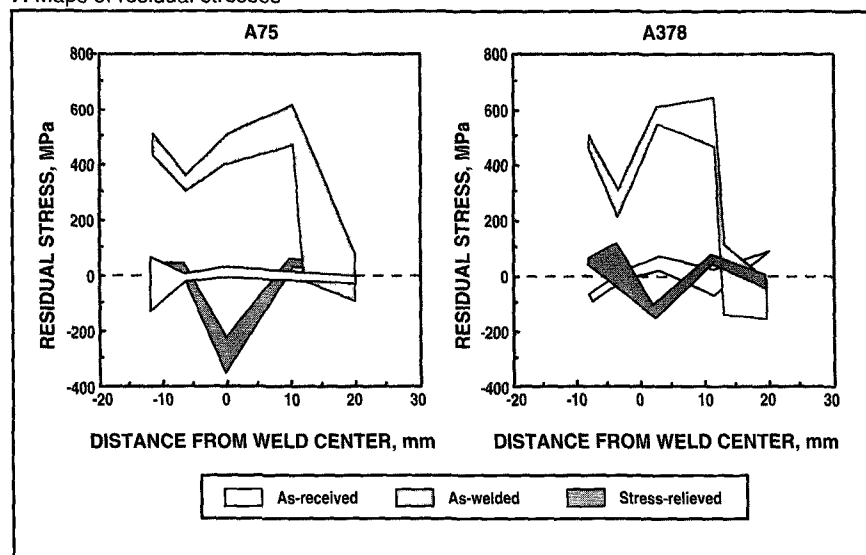
5. Rotating bending S-N data for duplex stainless steels A63 and A75



6. Alternating bending fatigue test results for duplex stainless steels A63 and A75



7. Maps of residual stresses



None of the S-N tests conducted under zero mean stress conditions revealed a significant difference in the 10^8 cycle fatigue limit for A63 and A75 despite the grossly different service performance records of these two materials. Figure 5 shows typical R. R. Moore data for the two most aggressive environments tested: 10,000 ppm Cl^- , 0 or 50 ppm $\text{S}_2\text{O}_3^{2-}$, pH of 1.0. There is a similarity of the corrosion fatigue lifetime despite different field service per-

formances. Typical data for the alternating bending tests yielded similar results as Fig. 6 shows. This figure indicates that the stress concentration of a drilled hole does not improve the predictive capability of the S-N test. Thus the presence of a stress concentration similar to that existing in actual suction rolls had little effect on the inability of S-N tests to predict service performance.

These results confirm that the corrosion fatigue lifetime of either smooth or notched specimens under fully reversed loading conditions does not accurately reflect gross differences in service performance of two duplex stainless steels. Furthermore, the utilization of a highly acidic, concentrated chloride test environment does not improve correlation between service performance of two duplex stainless steels and their fatigue limits. S-N tests employing a tensile mean stress may be necessary to simulate the high tensile residual stress thought to exist in A63 suction rolls.

Welding effects on suction roll performance

During the manufacture of suction roll shells, it may be necessary on occasion to repair casting defects revealed by machining or to remedy errors in the machining process. The suction rolls might therefore contain repair welds. In such cases, there are no reports on the appropriate welding practices used for different alloys and the effect of the weld on the subsequent resistance of the roll to corrosion-assisted

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cracking. If such welds are autogenous, i.e., without a weld filler metal, or if the welds do not have stress-relief, concerns may arise over the incidence of SCC near the welds. Although the small area of high residual stress in the weld location would likely constrain the SCC in such instances, such cracks might trigger corrosion fatigue crack growth, if the crack exceeds the critical flaw size for propagation (7, 8).

To examine this possibility, we imposed a severe test on samples of five of the duplex stainless steels listed in Table I to determine whether SCC cracking would occur near autogenous, nonstress-relieved welds. We placed ring welds approximately 20 mm in diameter on plate samples using a tungsten inert gas welding (TIG) torch without filler metal additions. The welding conditions were 200 A, 47 V, 6.4 mm/s travel speed, 2.4 mm electrode diameter, 4.8 mm working distance, argon shielding gas flowing at 20 ft³/min. We then placed some of these welded plates in a protective foil pouch for stress-relief at 550°C for 2 h followed by slow cooling to 425°C and subsequent air cooling to room temperature. We determined the magnitude and direction of the principal residual stresses near the welds, if present, by a careful hole-drilling technique for each of the three plate conditions: as-received, as-welded, and welded and stress-relieved. We next exposed samples of the three types to a 3000 ppm Cl⁻, pH 3 solution at 50°C for 1000 h to determine whether accelerated corrosion or cracking would occur.

As expected, each of the as-welded coupons exhibited very high tensile residual stresses near the ring weld with the peak stress occurring at the outer fusion line. We measured stresses as high as 660 MPa in these alloys. The differences in the peak residual stresses developed among the five as-welded materials were slight as Table III indicates. The peak residual stress in the wrought 3RE60 alloy was

8. Corrosion occurring in the vicinity of an as-welded specimen of A75



somewhat lower. The residual stresses measured on the as-received and welded and stress-relieved samples were small or were compressive in nature. Figure 7 shows an example of the residual stress maps for as-received, as-welded, and welded and stress-relieved samples of A75. For all the alloys tested, the fusion zone of the as-welded specimens exhibited the highest tensile residual stresses.

After exposure to the test environment, all the samples except A63 exhibited localized corrosion as well as some linear indications in the fusion zone of the weld. Figure 8 shows an example of the corrosion indicating the accelerated attack in a very aggressive test environment. There was no evidence of the tight, transgranular or intergranular SCC cracking often encountered in stainless steels following exposure to an acid chloride solution.

The implications for so-called "cosmetic" welding of flawed suction rolls are apparent but are of limited generality. Welding without stress-relief induces very high residual stresses near welds. It is possible to relax these stresses, however, with a moderate heat treatment following welding. Autogenous

welds are susceptible to corrosive attack in acid chloride solutions selected to simulate localized environments in pits and beneath deposits. The combination of the high residual stresses in the as-welded coupons and the aggressive test environment, however, was insufficient to introduce sharp cracks in the weld or the adjacent heat-affected zone of the weld. There were only broad "ditches" in the fusion zone of the weld. Although these were certainly of a length that exceeded the critical flaw size for fatigue crack propagation in these duplex stainless steels (8), the ditches were not sharp. It is unlikely that they would be effective in triggering corrosion fatigue crack growth at stress intensities near the threshold.

Because of the limited scope of the data available to date, the significance of welding, stress-relieving practices, or both in predicting service performance of suction roll materials is not clear. In an apparent contradiction with the service experience, the alloy with the lowest resistance to corrosion assisted cracking in service, A63, exhibited the greatest resistance to corrosion and development of crack-like fea-

tures during exposure to the acidic chloride environment. Whether this situation would occur in other test environments is unknown. It is clear, however, that the sequence of autogenous welding of suction roll alloys followed by exposure to an aggressive acidic chloride environment to encourage SCC is not a good predictor of service performance of suction roll alloys.

Conclusions

In the continuing search for a laboratory test that can accurately predict the resistance of suction roll alloys to corrosion-assisted cracking in actual service, the threshold stress intensity measurement continues to offer the best apparent correlation at least for cast materials. The results in this report and in earlier studies show that the threshold stress intensities for corrosion fatigue crack growth in a bronze and a cast martensitic stainless steel are lower than those of duplex stainless steels under the same conditions. This ranking is consistent with the broadly acknowledged susceptibility of these materials to corrosion-assisted cracking in service. The determination of a slightly higher threshold stress intensity for A86 offers an opportunity to test the validity of near-threshold fatigue testing as a predictor of subsequent service performance of suction roll alloys. The results reported here predict that A86 will be somewhat more resistant to corrosion-assisted cracking in service than A75.

S-N curves generated to date in a variety of aggressive test environments offer little assistance in discriminating between alloys with good and poor resistance to cracking in service. Increasing the corrosivity of the test environment did not improve the ability of S-N testing to predict service performance accurately. S-N tests in two very aggressive environments failed to reveal significant differences between A63 and A75, which occupy

opposite ends of the spectrum of resistance to cracking in service.

Limited tests on weldments in the duplex stainless steels used in suction roll applications show that residual stresses can be very high in these welds when there is no stress-relief treatment following welding. Although these stresses were very high, exposure of welded, but not stress-relieved, coupons to an aggressive acid chloride environment did not induce SCC. The fusion zones of most of the coupons did exhibit accelerated corrosion in these aggressive environments, however, regardless of heat treatment. Since A63 exhibited the best resistance to such corrosion, the tests conducted on the weldments do not offer improved ability to predict service performance. ■

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