Influence of nondestructive test procedures on detection of stress-corrosion cracks

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ABSTRACT: A weld "T" joint from a scrapped carbon-steel digester level tank was used to test the efficacy of the nondestructive liquid-penetrant and magnetic-particle test methods commonly used for field detection of stress-corrosion cracks. The tests were conducted using three methods of surface preparation—wire brushing, light grinding, and sandblasting. Light grinding of the surface greatly increased the sensitivity of both the liquid-penetrant and magnetic-particle test methods. The most successful combination was light surface grinding followed by inspection with a fluorescent liquid.

KEYWORDS: Alloy steel, Canada, carbon steel, commonwealth, corrosion, cracks, detection, joints, nondestructive tests, North America, stainless steel, stresses, surface treatment, test methods.

This report describes the results of tests carried out to document the influence of surface preparation and nondestructive test methods on the ability to detect stress-corrosion cracks (SCC). Our experience has taught us that some removal of surface metal is required to maximize detection of stress-corrosion cracks in both carbon steel and austenitic stainless steels. In field conditions, this requirement is best met by light surface grinding. However, grinding is sometimes objected to because of the belief that grinding either causes cracks or causes cracks to run. Our experience indicates that this belief is untrue for the austenitic stainless steels and low-carbon pressure-vessel steels commonly used in the pulp and paper industry.

On the other hand, it is commonly believed that power wire brushing or sandblasting are adequate for surface preparation. Our experience indicates that surface preparation by power wire brushing can reduce the sensitivity of the liquid-penetrant and magnetic-particle test methods commonly used to detect stress-corrosion cracking. Severe cracking will likely be detected in carbon steels if magnetic-particle testing is used, but fine cracks can be missed. Thus wire brushing preselects the size of the defect that can be found. For austenitic stainless steels, the use of power wire brushing for surface preparation can result in nondetection of even severe stress-corrosion cracking.

Surface preparation by sandblasting is not a common practice for field inspection of pulp and paper equipment in our locality. Nevertheless, based on our limited experience, we believe that sandblasting also reduces the ability to detect stress-corrosion cracking on carbon steels, compared with surface preparation by light grinding.

Sandblasting is often used prior to shop inspection of rebuilt equipment. It has also been approved for follow-up field inspections by the National Association of Corrosion Engineers (NACE).[1] The NACE document recommends grinding of weld toes for initial inspection but allows sandblasting for follow-up inspections unless weld-toe corrosion necessitates regrinding. The NACE document also cautions that "improper surface grinding resulting in overheating . . . can cause additional cracking." As we have already noted, our experience shows this to be an extremely rare problem with common pulp and paper industry

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[1] "Recommended practice for prevention, detection and correction of deaerator cracking," NACE Standard RP0590-90, National Association of Corrosion Engineers, Houston, 1990, p. 6.

steels when grinding has been done for inspection. Grinding done for repair work may indeed be overdone.

The extension of field experience gained from a wide range of inspection situations to general guidelines is difficult. Inevitably, conflicting field experiences will be cited. Mill engineers can receive contradictory opinions from nondestructive-testing personnel, consultants, insurance companies, and their own maintenance tradesmen. It is difficult to exercise sound engineering judgment based on opinions that often are unsubstantiated. This report is an attempt to contribute some specific examples to aid mill engineers in their decision making.

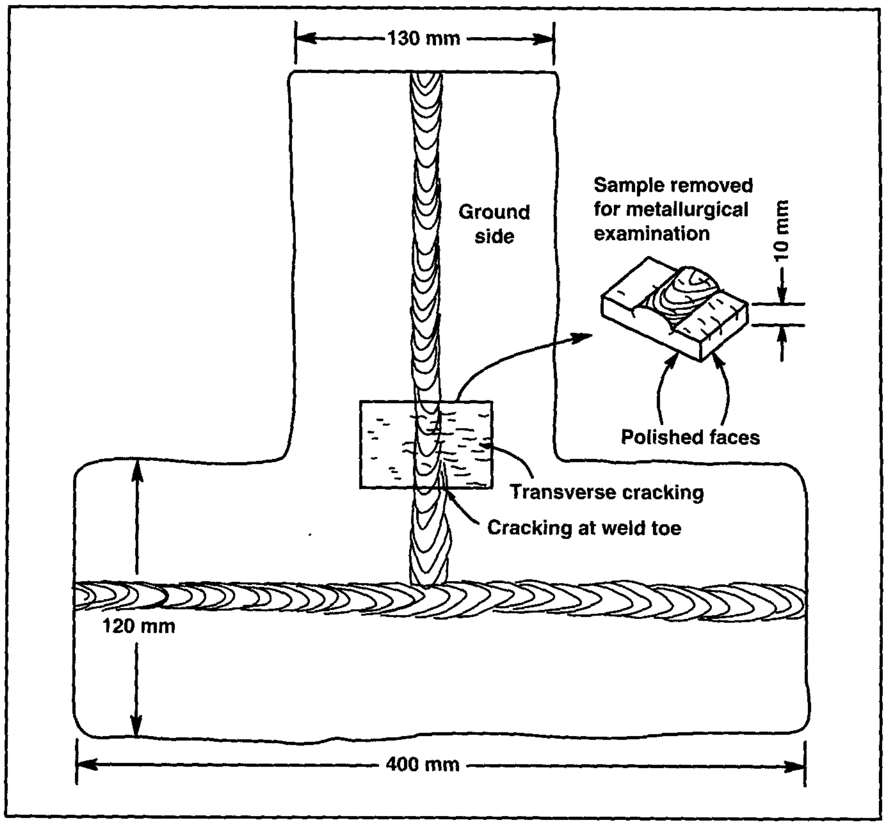
Carbon-steel level tank

History of test piece

A weld "T" test piece was cut from a carbon-steel Kamyr digester level tank that had been scrapped because of stress-corrosion cracking. The tank was put into service in 1963. In 1986, selected areas of welds were ground and inspected via WFMT (wet fluorescent magnetic-particle testing). Cracks were found, and several areas were ground clear of cracks. In 1989, the ground areas were wire brushed and reinspected with a method that uses black magnetic ink on a white background. Cracks had reappeared where they had been ground out in 1986. Grinding revealed the reinitiated cracking had penetrated to ≈ 1/8 in. Since the bulk of the vessel had not been inspected, and since reinitiation in the ground area indicated that cracking continued to be active, the mill decided to replace the vessel at the next maintenance shutdown. Post-weld heat treatment (stress relief) was specified for the replacement vessel.

When the scrapped vessel was removed, a weld "T" section was cut out to verify the cracking mechanism. The opportunity was also taken to compare the ability of the various test procedures commonly used to locate stress-corrosion cracks.

1. Drawing of weld "T" showing location of metallurgical specimen



Metallurgical examination

Figure 1 is a drawing of the weld "T" that was removed from the scrapped level tank. A sample was cut from the weld, as illustrated in Fig. 1. The four faces of the sample were polished for metallographic inspection. Cracking was confirmed both transverse to the weld and parallel to the weld toe.

Figure 2 shows a cross section through a transverse crack. All transverse cracks observed were intergranular in nature, typical of caustic SCC.

Figure 3 shows a cross section through a weld toe crack. While cracking was visible only at the ground weld toe, both weld toes were found to be cracked. Again, cracking was intergranular. Because cracking followed the boundary between weld and parent metal, a micro hardness transverse was carried out. Average hardness was 132 Vickers (119 Brinell) in both weld metal and parent plate. There was no increased hardness associated with the cracking.

Test procedure

Table I lists the nondestructive test procedures performed in the sequence of their performance.

The chosen tests were representative of those that are commonly used (or could be used) to inspect vessels such as level tanks. Not all possible tests were carried out, and each test method was tried at one standard sensitivity level. For instance, yoke magnetization was carried out with ac current only, and prod magnetization was carried out with dc current only. Other possible current types and current strengths were not compared. Similarly, we did not compare varying dwell times or temperatures with liquid penetrants, nor did we test post-emulsifiable penetrants. We also did not attempt to compare equipment or consumables from different manufacturers.

Eleven test methods were carried out on the right-hand side of the "T" prior to grinding the right-hand test surface. Following grinding of the

I. Test numbers for the 29 combinations of test procedure and surface-preparation method

Test procedure*		Surface-preparation method: *Wire brushed*	*Lightly ground*	*Sand blasted*
Visual inspection		1	12	21
Dry MPI	Yoke magnetization	2	13	22
	Prod magnetization	3	14	23
Dry red	MPI on white background			
	Yoke magnetization	4	...	...
	Prod magnetization	5	...	...
Wet black	MPI on white background			
	Yoke magnetization	6	15	24
	Prod magnetization	7	16	25
WFMT	Yoke magnetization	8	17	26
	Prod magnetization	9	18	27
LPI		10	19	28
	Visible fluorescent	11	20	29

*MPI = magnetic-particle inspection; LPI = liquid-penetrant inspection; WFMT = wet fluorescent magnetic-particle testing.

right-hand side, 9 of the 11 test methods were carried out again. A small rectangular sample was then cut from the test piece for metallographic examination of the cracks.

The entire test surface was then sandblasted with a typical metal-cleaning-type blast. Following the sandblasting, nine test methods were again carried out on the test surface. We attempted to ensure that the variable conditions for the test methods remained as consistent as possible. Following all of these tests, the test area was lightly ground on both sides of the weld and tested with fluorescent penetrants to confirm the presence of cracks throughout the test area.

All tests were conducted at room temperatures and in accordance with Standard ASME/ASTM test procedures. The test piece was cleaned between tests, when necessary, with solvent cleaners.

Magnetic-particle test procedures were carried out in accordance with ASME/ASTM SE 709—Standard Practice for Magnetic Particle Examination. For both the yoke and prod methods, the tests were carried out and compared using the continuous magnetization technique. Liquid penetrant procedures were carried out in accordance with ASME/ASTM SE 165—Standard Practice for Liquid Penetrant Inspection Method.

The test results were photographed at each stage of the test program with lighting and camera angles as consistent as could reasonably be achieved in an industrial shop environment.

Equipment and materials

The yoke used for the magnetic-particle testing was a Magnaflux Y7 alternating-current electromagnetic yoke with a lifting force of at least 10 lb. For prod magnetization, a prod spacing of 6 in. was used with a dc current of 100 Amps per inch of spacing. The dry powder used was Magnaflux 8A red powder; the wet fluorescent magnetic-particle suspension was Magnaflux 14A powder in a bayol base at a concentration of 0.1 mL/100 mL; the wet black suspension was Ardrox 800/3 aerosol mixture on a background of Ardrox Pyrene 8386W aerosol contrast-aid paint. The liquid penetrant materials used were all Met-L-Chek aerosol materials as follows: VP30 visible water-washable penetrant; FP95A solvent-removable fluorescent penetrant; E59 remover; R501 cleaner/remover; and D70 developer.

Results

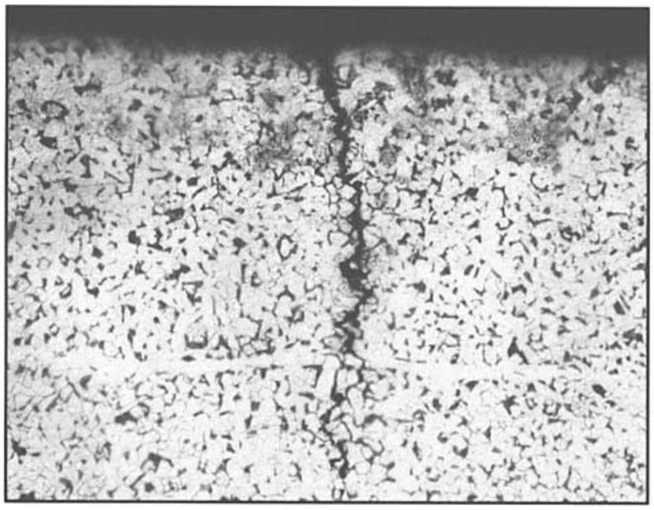
The tests were compared based on their ability to reveal cracks. Test procedures that revealed more cracks received a lower numerical rating than procedures that revealed fewer cracks. For the magnetic-particle tests, the yoke or the prods were applied in a position that would reveal the most cracks. In comparing the results, we allowed for the fact that the magnetic-particle tests could reveal additional cracks if applied at varying positions. Only cracks appearing within a small test area were considered for the comparison purposes. **Table II** summarizes the results.

Of the 29 test methods applied (including three visual inspections), six failed to produce any identifiable crack indications, as seen in Table II. These six methods were rated last, 16 out of 16. The remaining 23 methods revealed from 1–2 cracks to 225–275 cracks and were rated from 15 up to 1.

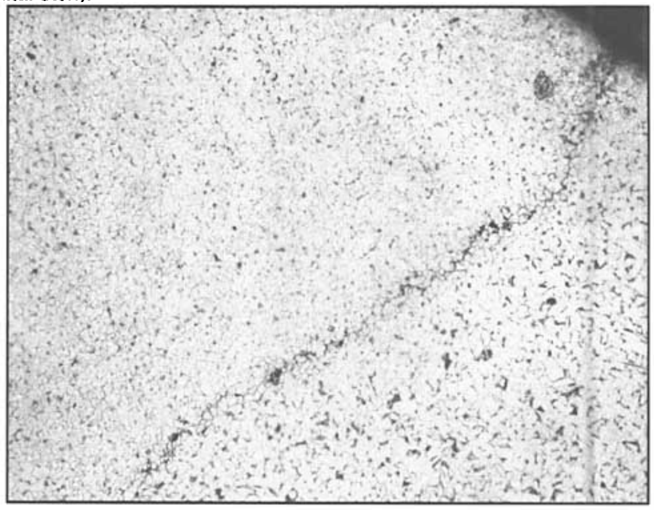
As seen in **Table III**, surface preparation had a significant effect on test sensitivity. The six most sensitive methods all involved light grinding for surface preparation. Grinding of the surface significantly improved all of the test results, with the exception of visual examination. For example, the solvent-removable fluorescent LPI test with no grinding (i.e., with wire brushing or sandblasting) was among the least sensitive methods. In combination with light grinding, this method was the most sensitive of all the tested methods.

In general, sandblasting was the least successful surface preparation for

2. Cross section of stress-corrosion crack transverse to the weld toe (200x, 2% nital etch)



3. Cross section of stress-corrosion crack parallel to and through the weld toe. Weld heat-affected zone is to the left of the crack (125x, 2% nital etch).



testing. The most sensitive method with sandblasting (WFMT with prod magnetization) rated 13th, with only 3 or 4 cracks detected.

Figures 4 and 5 show the results for the two most sensitive test methods, light grinding followed by either fluorescent LPI or WFMT with prod magnetization. The most sensitive techniques revealed extensive cracking running at 45°. Less sensitive techniques detected only the transverse cracks in the weld cap. Note that in both figures, the left side of the "T" was left as received. It had, however, been wire brushed during the 1989 inspection of the vessel and immediately upon removal from the vessel in 1990. The weld toe on the left-hand side was unground. The grinding marks visible on the left-side parent metal may have dated from vessel fabrication.

For comparison, **Figs. 6 and 7** show the results for wire brushing followed by either WFMT or black MPI on a white background. These tests were less sensitive but still detected transverse cracking of the weld cap.

Figure 8 shows the weld "T" after completion of the test program. The entire surface was lightly ground and tested by fluorescent LPI. Cracking in parent plate at 45° to the welds is readily apparent on the left-hand side. This cracking was not detected when only sandblasting was used for surface preparation. The known indications on the right-hand side (apparent in Figs. 4–7) are not visible here because the incidence angle of the black light resulted in glare.

Austenitic stainless steels

Belt-type brownstock washer

Internal inspection of a belt-type brownstock washer after only about 80 days of operation revealed severe pitting of types 304L and 316 stainless steel under deposits of black liquor and fiber carried through the vapor system. The mill was located on the West Coast, and a significant portion of the wood supply was sea floated. Typical deposits extracted in boiling water produced a pH of 5.6 and contained 4500 ppm water-extractable chloride ion based on oven-dried solids. After a further 30 days of operation, several feet of a roof-mounted vapor diffuser collapsed from massive stress-corrosion cracking of the 304L stainless steel. Type 316 instrument tubes used to spray observation windows leaked because of SCC.

On a subsequent shutdown, it was decided to inspect all areas covered by deposits for SCC. The method chosen was surface preparation by power wire brush followed by water-washable color-contrast liquid-penetrant inspection. Areas of through-wall cracking in the thin-gauge vapor hood were readily detected. The thick-walled support pipes for internal showers were found to be indication free. This result was judged to be questionable, so light grinding was used to prepare the surface. Severe SCC was detected, as shown in **Fig. 9**. The orientation of cracking clearly reflects the residual and service stresses present at the welded joint and is in no way related to grinding. The SCC that will eventually threaten the structural integrity of the supports would have gone undetected if power wire brushing had been relied on for surface preparation.

Other examples

This experience with a brownstock washer is only the latest among several examples where reliance on wire brushing would have led to nondetection of SCC. Other examples include:

- Internal SCC of 904L CTMP pressurized presteaming tubes
- External SCC of type 304L causticizer tanks
- External SCC of type 304L evaporator heads
- External SCC of a type 304L Kamyr digester presteaming vessel

II. Ratings for the 29 combinations of test procedure and surface-preparation method

Rating [a]	Test no.	Surface-preparation method	Test procedure	No. of cracks [b]
1	20	Lightly ground	LPI—fluorescent	225 to 275
2	18	Lightly ground	WFMT—prods	200 to 250
3	16	Lightly ground	Wet black MPI on white—prods	120 to 150
4	15	Lightly ground	Wet black MPI on white—yoke	115 to 145
5	17	Lightly ground	WFMT—yoke	100 to 130
6	19	Lightly ground	LPI—visible	80 to 90
7	9	Wire brushed	WFMT—prods	60 to 70
8	8	Wire brushed	WFMT—yoke	45 to 50
8	14	Lightly ground	Dry MPI—prods	45 to 50
9	7	Wire brushed	Wet black MPI on white—prods	30 to 40
10	13	Lightly ground	Dry MPI—yoke	25 to 35
11	6	Wire brushed	Wet black MPI on white—yoke	20 to 30
12	5	Wire brushed	Dry red MPI on white—prods	6 or 7
13	27	Sandblasted	WFMT—prods	3 or 4
13	4	Wire brushed	Dry red MPI on white—yoke	3 or 4
14	25	Sandblasted	Wet black MPI on white—prods	1 or 2
14	24	Sandblasted	Wet black MPI on white—yoke	1 or 2
14	29	Sandblasted	LPI—fluorescent	1 or 2
14	26	Sandblasted	WFMT—yoke	1 or 2
14	23	Sandblasted	Dry MPI—prods	1 or 2
14	22	Sandblasted	Dry MPI—yoke	1 or 2
14	3	Wire brushed	Dry MPI—prods	1 or 2
15	21	Sandblasted	Visual inspection	1
16	28	Sandblasted	LPI—visible	0
16	12	Lightly ground	Visual inspection	0
16	11	Wire brushed	LPI—fluorescent	0
16	10	Wire brushed	LPI—visible	0
16	2	Wire brushed	Dry MPI—yoke	0
16	1	Wire brushed	Visual inspection	0

[a] No. 1 is the most sensitive of 29 combinations; no. 16 is the least sensitive of 29 combinations.
[b] The reported results should not be interpreted as accurate counts of crack indications. Rather, the numbers indicate the general ability to locate cracks within the test area for a given combination of test procedure and surface-preparation method.

III. Sensitivity of test procedures as a function of surface-prepartion method

Test procedure	Surface-preparation method: Lightly ground	Wire brushed	Sand blasted
LPI—fluorescent	1	16	14
WFMT—prods	2	7	13
Wet black MPI on white background—prods	3	9	14
Wet black MPI on white background—yoke	4	11	14
WFMT—yoke	5	8	14
LPI—visible	6	16	16
Dry MPI—prods	8	14	14
Dry MPI—yoke	10	16	14
Dry red MPI on white background—prods	...	12	...
Dry red MPI on white background—yoke	...	13	...
Visual inspection	16	16	15

Metallurgical samples removed from the 904L CTMP vessel and the evaporator head confirmed the presence of chloride SCC, which was in no way related to grinding either in terms of initiation or extension.

Discussion

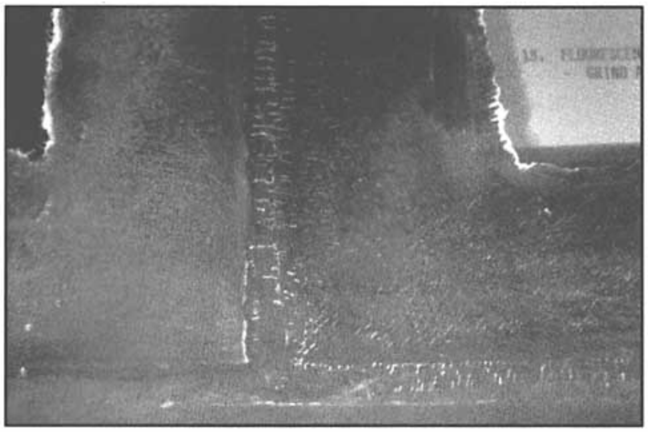
The information presented in this paper is intended to demonstrate that, in specific situations, detection or nondetection of stress-corrosion cracking is strongly dependent on surface preparation and test technique. The findings are not meant to be generalized or applied out of context.

The most important point is that a report of "no indications" may not mean no cracking. It is necessary for engineers interpreting inspection results to assure themselves that the methods used, including surface preparation, are appropriate for the level of sensitivity desired. In the case of carbon-steel pressure vessels like digesters or level tanks, the choice of surface preparation and test technique can be a means of preselecting relevant defects. That is, minor defects may not be detected, and if they are not detected, they need not be dealt with. For example, power wire brushing followed by WFMT or black MPI on a white background might be chosen for reinspection of a digester. In the absence of weld-toe ditching, this procedure would detect significant cracking. However, it might not detect minor SCC.

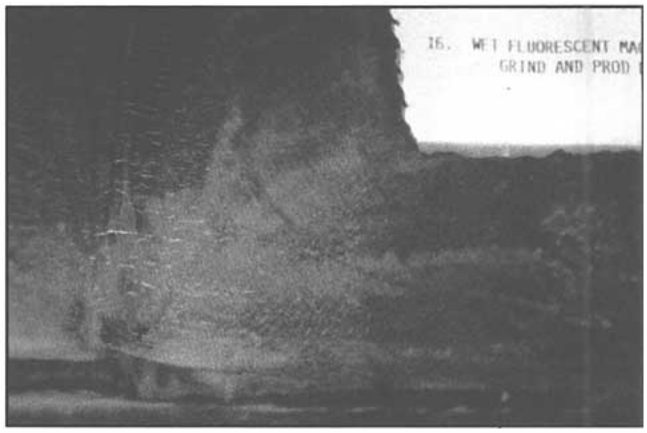
Sandblasting does not appear to be a good surface-preparation technique unless the objective is to detect very severe cracking.

For inspection of austenitic stainless steels, it appears prudent to at least require light grinding of selected areas to ensure SCC is not missed. Our experience indicates that fears of causing crack initiation in subsequent service or of causing existing cracks to run are unfounded, provided that reasonable care is taken in grinding. It seems probable that most stories of grinding "causing" cracking in austenitic stainless steels have originated

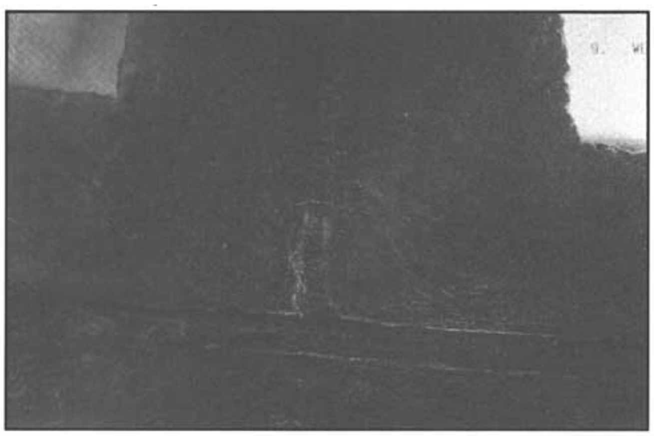
4. Lightly ground, followed by solvent-removable fluorescent LPI. Bright, clear indications of cracks are visible in the ground areas of both weld caps. Clear indications of horizontal cracks are visible on the right-hand side up to 1.5 in. from the vertical weld, with 45° cracks visible up to 3 in. from the welds. No relevant indications are apparent in the nonground areas.



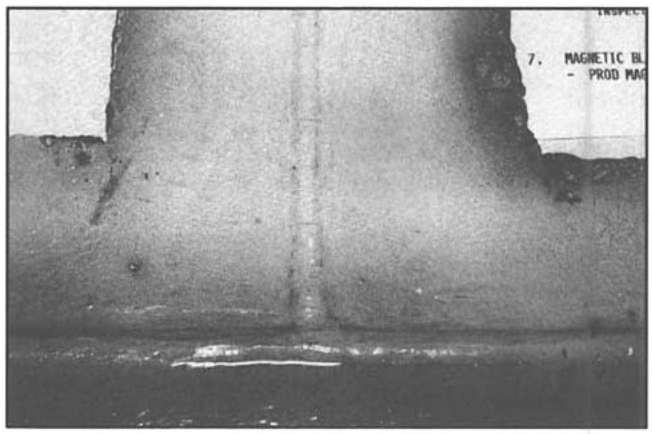
5. Lightly ground, followed by WFMT. Clear indications of cracks are visible in the ground area on the right-hand side. In the nonground area on the left-hand side of the vertical weld, cracks were visible up to 1 in. from the vertical weld.



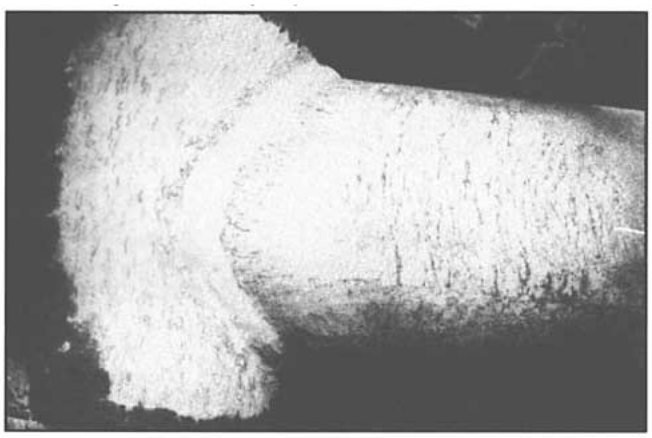
6. Wire brushed, followed by WFMT with prod magnetization. Clear indications of cracks are visible in the weld cap and in the weld's heat-affected zones. Faint indications of cracks at 45° to the welds are visible on the right-hand side.



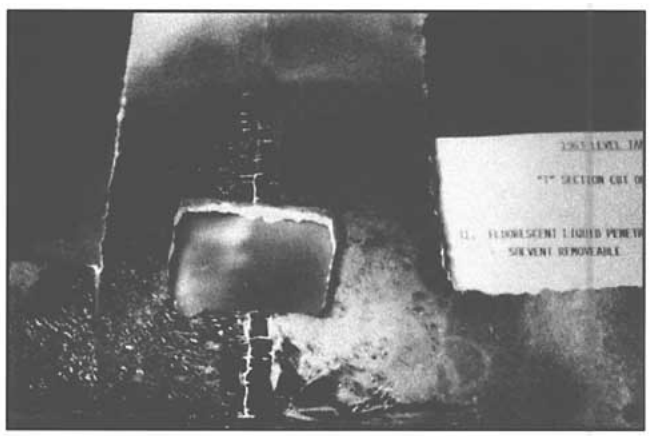
7. Wire brushed, followed by black MPI on white background. Clear indications of cracks are visible in the weld cap and in the weld's heat-affected zones. A few cracks are visible in the parent plate up to 0.5 in. from the vertical weld.



8. Lightly ground, followed by solvent-removable fluorescent LPI. The entire surface was sandblasted, tested, then lightly ground for the final, highest sensitivity inspection



9. Chloride SCC in Type 304L stainless-steel shower support. Light grinding was required to detect cracking via visible solvent-removable LPI



because grinding made existing cracks detectable. Wherever we have removed metallurgical samples from stress-corrosion-cracked austenitic stainless steels, we have found only normal SCC, even when heavy grinding has been used to explore the cracking.

Conclusions

In the specific contexts dealt with, it is concluded that:

1. Surface preparation before inspection has a significant influence on the sensitivity of nondestructive examination techniques.
2. Some degree of surface metal removal is required to maximize inspection sensitivity for SCC in both carbon steels and austenitic stainless steels.
3. Light grinding is the best means of surface preparation if maximum test sensitivity is desired.
4. Light grinding for inspection does not cause existing cracks to run, nor does it promote crack initiation in subsequent service.

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