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MICROBIOLOGICALLY INFLUENCED CORROSION TESTING OF WELDED STAINLESS ALLOYS FOR NUCLEAR POWER PLANT SERVICE WATER SYSTEMS

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ABSTRACT

Field tests in microbially active waters were conducted with several austenitic stainless alloys in various welded conditions. The metallurgical, environmental and process design factors that influence MIC in service water systems are discussed. Recommendations for conducting MIC tests of fabricated pipe and tubing are offered.

Keywords: Stainless steels, Microbially Influenced, Corrosion Testing, Welding, Fabrication, Corrosion, Nuclear Power Industry

INTRODUCTION

The metabolic products of microorganisms appear to directly affect certain materials of construction, such as mortar and carbon steel, but corrosion resistant materials, such as stainless steels, appear to be affected more indirectly by the presence of microbes. The role of microbes in the corrosion of stainless steels appears to be related to the ability of microbial consortia to concentrate, sometimes with remarkable efficiency, certain aggressive chemical species, such as chloride, sulfide and permanganate ions, at sites that are deaerated and reducing. What makes MIC unique is that in addition to changing local surface chemistry by depleting and/or concentrating certain chemical species in the bulk environment, microorganisms can actually transform certain chemical species normally

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present in the water into other more aggressive forms that would not otherwise be present (e.g. Fe^{2+} to Fe^{3+} , Mn^{2+} to Mn^{4+} , S^0 to S_x^{2-}).^{1, 2} and create species that would not otherwise be present. The mere presence of a biomass on a passive surface creates an inhomogeneous diffusion barrier between the metal surface and the bulk environment that can occlude localized sites and even create new ones for electrochemical reactions. The transfer of charge between microbes, metal ions and surfaces (e.g. exopolymer adherence to a metal surface) can also result in direct attack. Finally, the accumulation of inorganic matter, particularly corrosion products, within a biomass can significantly alter anodic and cathodic reactions so as to initiate and, more importantly, sustain the propagation of a pit.

A reliable method for determining the "MIC resistance" of various alloys has yet to be standardized. It has proven to be very difficult to reproduce the population dynamics of microbial consortia in natural waters so as to accelerate corrosion in a reproducible manner. Compared to a chemical corrosion test, the methods for obtaining, isolating, definitively characterizing and maintaining active cultures for MIC tests require highly specialized skills, much expensive equipment and is very labor intensive. Even among the few organizations that have overcome these experimental difficulties, controversy still reigns over what specific microorganisms, or groups of microorganisms, and environmental conditions should be used in a laboratory "MIC test" in order to be relevant to industrial processes. One of the few things that metallurgists, microbiologists and corrosion scientists agree upon is that it is very difficult to directly establish cause and effect relationships in MIC tests.

It appears unlikely that a single representative test for evaluating the "MIC resistance" of materials will be established given the diversity of the environments in which MIC occurs. Conversely, the tremendous range of conditions that can occur in real process streams (or side loops) means that data from field tests may be site specific and may only be representative of a given site for a limited period of time. From the standpoint of materials performance, the "MIC resistance" of an alloy must be qualified in terms of specific factors that accelerate corrosion in order to have practical value. Much progress has been made in understanding the means by which microorganisms can create conditions that degrade materials of construction, but more work has to be done in order to identify the metallurgical factors that influence the resistance of alloys under such aggressive conditions.

Resolving MIC problems requires interdisciplinary cooperation to adequately address the complexity of three highly specialized paradigms: Microbiology, Metallurgy and Corrosion Science. Our present understanding of MIC is often biased by anecdotes and misconceptions promoted by experts (and non-experts) in one field attempting to interpret the results of other disciplines.* This is particularly true of studies involving sophisticated electronic apparatus for *in situ* measurements (refer to a recent review by Mansfeld and Little³).

The purpose of this paper is to evaluate the MIC resistance of austenitic stainless steels in various welded conditions to raw water known to induce MIC. Welded pipe sections were exposed to raw water under low flow conditions at ambient temperature.

* The present work does not represent an exception to this trend.

Corrosion and Microbiology

At a very fundamental level, microbes can be seen as influencing corrosion because the processes involved in microbial metabolism and corrosion both involve charge transfer reactions. The concept of an electron acceptor and donor are crucial to both corrosion and microbiology. (In corrosion reactions, an electron acceptor acts as a cathode relative to an anode, or electron donor.) As with corrosion, the metabolism of living microorganisms involves oxidation-reduction processes accompanied by a release of energy.⁴

There are many proposed mechanisms for MIC based on an understanding of the responses of organisms to various stimuli and the conditions resulting in the degradation of materials. For example, steels are known to corrode by differential aeration at occluded surface regions. Corrosion is accelerated because the oxygen that is essential to the stability of a passive film is prevented from diffusing to the occluded site. It has been proposed^{5, 6, 7} that biofilms and tubercles can greatly accelerate this process by not only acting as a physical barrier to the diffusion of oxygen but also by consuming oxygen in the metabolism of aerobic bacteria. Under these oxygen-depleted conditions in the biofilm, anaerobic bacteria will grow by using certain chemical species, such as sulfates or nitrates, as the electron acceptors. Certain "facultative" bacteria can adapt and grow under dynamic conditions by using alternate nutrient sources once one has been depleted.^{4, 8} Differential aeration cells also provide excellent conditions for the growth of sulfate-reducing bacteria, such as *Desulfobacter*.

Pseudomonas, *Sphaerotilus*, and *Desulfovibrio* are often associated with corrosion of stainless steels.⁹ Filamentous bacteria, such as *Sphaerotilus*, *Crenothrix*, *Leptothrix*, and *Gallionella* can oxidize ferrous (Fe^{+2}) ions to ferric (Fe^{+3}) ions which leads to the rapid accumulation of ferric hydroxide⁹ and, in the presence of chlorides, the formation of ferric chloride. This process has led to attack of stainless steels in environments that were regarded as chemically benign.^{10, 11, 12} The relative resistance of austenitic stainless steels to ferric chloride varies as a function of alloy content, particularly the molybdenum, chromium and nitrogen contents (Table 1).

Bacteria have indirectly caused the corrosion of stainless condenser tubing by oxidizing manganous (Mn^{+2}) ions to manganic (Mn^{+3}) ions.^{1, 13} The *Thiobacillus thiooxidans* species produces H_2SO_4 as a metabolic product which can directly increase the corrosion rate.^{14, 15, 16, 17}

Conditions for Microbial Growth

MIC can only be defined in terms of specific cases because of the great physiological diversity of microorganisms present in natural waters¹⁸ and the wide range of environmental conditions to which consortia of microbes can adapt. Microorganisms can tolerate high pressures, as well as a wide range of temperatures, pH values and oxygen concentrations.¹² This means that large populations of microorganisms will remain in water and biofilms even after conventional water treatments. Microorganisms readily adhere to almost any surface in contact with natural waters.¹⁹ Many microorganisms

secrete reactive exopolymers that can adhere to metal surfaces and bind organic and inorganic debris into tubercles.^{20, 21} Once a microbial substratum is established, environmental and physical factors such as water chemistry, temperature, and surface roughness of the substrate affect further attachment of organisms in the biofilm. In addition, nutrient sources, interactions between various species of microbes and flow shear effects play important roles in the growth of a microbial consortium. It is because of these factors that the localized conditions at a metal surface under a biofilm can be quite different than that in the bulk water. A reliable assessment of the potential for MIC in a system must focus on conditions at the metal surface. Bulk water analysis is at best an indicator of the activity of mobile microorganisms. Much work continues to be done to develop more reliable techniques to identify and measure the chemical characteristics of a biomass that result in MIC.

Metallurgical factors

Weldability. The fabrication of service water piping systems requires extensive on-site welding. Because of their resistance to attack by water, steam, steam condensate, ammonia, and oxygen, austenitic stainless steel alloys of AISI Types 304L and 316L are often selected for welded pipe, tubing and vessels.²² These grades are the most weldable of the AISI 300 series austenitic stainless steels. The basic compositions and some important properties of the alloys discussed above are listed in Tables 2 and 3. The intrinsic corrosion resistance of these alloys can be maintained in the welded condition by:

- Using over-alloyed filler metals and base metals that have compositions balanced to inhibit the formation of unwanted phases and cracking during welding
- Controlling the heat input and mixing of the weld and base metal
- Shielding molten and hot metal surfaces with inert gases
- Removing heat-tints and other surface contamination and damage due to fabrication

Guidelines for optimizing the corrosion resistance of welded stainless structures are available from several sources.^{23, 24, 25, 26} However, these recommended practices do not consider all the important aspects of specifying, fabricating and finishing.

Weld microstructure. The regions within a weld can be described in the following terms, as illustrated in Figure 1:²⁷

- Composite Zone-The bulk of the weld bead consisting of filler metal that has been mechanically mixed with melted base metal and, consequently, altered in composition.
- Unmixed Zone-The zone at the outer edge of the weld metal consisting of base metal that has melted but not mechanically mixed with filler metal prior to solidification.
- Weld Interface-The surface bounding the region of base metal that had completely melted during welding as characterized by a definite solidification substructure.
- Partially Melted Zone-The portion of the base metal located just outside the weld interface within which the degree of melting ranges from 0 to 100%.
- True Heat-Affected Zone (HAZ)-The portion of the base metal within which microstructural changes have occurred but in the absence of melting.

Sensitization. It has long been established that austenitic stainless steel with carbon contents below about 0.030 wt% are not "sensitized" to intergranular corrosion.²⁸ Minor additions of Ti, Nb and Ta function as "stabilizers" by preferentially combining with carbon, thus avoiding chromium carbide precipitation.²⁸ Molybdenum and nitrogen act to increase the level of carbon and heat that can be tolerated by an austenitic stainless alloy, such as AL-6XN® alloy. The maximum interpass temperature of stainless steel welding procedures are usually limited to 180°C (350°F) to minimize sensitization.

In addition to ferrite and carbides, the sigma and chi phases may be present in molybdenum-bearing austenitic stainless steel weldments. In the case of sensitized AISI Type 316 weld metal²⁹, a 50% increase in the Cr and a 300% increase in the Mo content occurs for sigma phase and the chi phase is increased by 28% Cr and 550% Mo relative to the bulk. Consequently, the regions immediately surrounding these precipitates are chemically depleted and more susceptible to preferential attack in certain environments. Continuous intergranular networks of sigma phase reduce the toughness, ductility and corrosion resistance of stainless steels.³⁰ Nitrogen is used in some commercial alloys to suppress the formation of deleterious phases and, in cooperation with chromium and molybdenum, to improve localized corrosion resistance.^{31, 32, 33, 34, 35}

Over-alloyed Filler Metals. Welds made with filler metal compositions that match the base metal generally have lower corrosion resistance than fully annealed base metal due to lack of homogeneity and microsegregation of chromium and molybdenum. Such chemically depleted regions can be much more susceptible to localized attack in certain environments.³⁶ Figure 2 shows localized corrosion at interdendritic regions of an ER 308L weld made in Type 304 pipe induced by microbially active water. The use of over-alloyed (over-matched) filler metals are recommended³⁶ to compensate for chemical segregation in the weld bead unless a post weld solution anneal is performed.

Weld Unmixed Zones. Unmixed zones are a concern because such regions have the bulk composition of base metal but a microstructure that is similar to an autogenous weld. Microsegregation and precipitation phenomenon characteristic of autogenous weldments decrease the corrosion resistance of an unmixed zone relative to the parent metal.³⁷ Unmixed zones bordering welds made from over-alloyed filler metals can be preferentially attacked when exposed on the weldment surface.^{36, 38, 39} The potential for preferential attack at unmixed zones can be reduced in field construction by:

- (1) Maintaining a constant and adequate supply of filler metal to the weld gap
- (2) Proper fixturing (particularly, maintaining the minimum weld root gap)
- (3) Maintaining heat input to achieve full penetration
- (4) Using filler metal inserts
- (5) Post weld solution annealing.

Heat Tints. In fabricating a pipeline, a heat tint would most likely result from the oxidation of the ID surface of a pipe due to some defect in the purging system or procedure. The defects, internal stresses and composition of the heat-tint oxide make it a poor barrier to any corrosive media. In addition, the chromium-depleted layer of base metal beneath

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the heat tint is significantly less resistant to localized corrosion than the base metal. The corrosion of the heat-tint oxide can also activate the metal beneath it in a manner similar to free iron particles on a surface.

Whether a weld heat-tint should be removed prior to service depends upon the given alloy and service environment. Preferential corrosion at heat-tinted regions is most likely to occur where an alloy performs near the limit of corrosion resistance. The corrosion resistance of heat-tinted regions can be restored by grinding and/or pickling.⁴⁰ In the preferred two step operation, the heat-tint oxide and chromium-depleted layer are first removed by grinding. The abraded surface is then cleaned with an acid solution (nitric-hydrofluoric or phosphoric acid) or a pickling paste. After a sufficient contact time, the acid-cleaning solution or paste is thoroughly rinsed with water, preferably with a low chloride-ion content.

EXPERIMENTAL

Materials and Fabrication

The test program was undertaken in two phases:

- Phase I: AISI Types 304L and 316L ASTM A 312 grade pipe was GTAW welded with Type ER 308L and E 312 filler metals. Filler metal compositions were varied to achieve low, medium, and high ferrite numbers in the as-welded bead.
- Phase II: Alloy 904L and AL-6XN alloy were welded with nickel base filler metal wires, inserts and coated electrodes by Trent Tube-Carrolton, GA Works and B. F. Shaw, Inc., Laurnes, S.C. Dissimilar metal joints were also prepared from AL-6XN and Type 316 pipe sections with Alloy 625 filler.

The complete matrix of sample conditions appears in Table 4. The compositions of pipe and filler metals used are listed in Table 2.

A total of nine multi-pass circumferential welds were made in each pipe. Various filler metals and weld metal inserts were used in either a manual gas tungsten-arc welding (GTAW) or an automated gas metal-arc welding (GMAW) process. Certain sub-assemblies in each pipe were post-weld annealed and pickled and others were just pickled prior to final assembly. All of the pipe sections were split longitudinally in half, end-capped and fitted with inlet and outlet lines to form "troughs" (Figure 3). The troughs were tightly fitted with metal lids. In this way, the ID surface of the pipe could be observed during exposure without interrupting the flow of water through the pipe. Defective welds were also prepared in AL-6XN pipe for comparison. The defective sections had a single weld that either had been incompletely penetrated, was heat tinted, or had less than the minimum weld gap.

Field Exposures

The troughs in Phase I were taken to a field site and exposed outdoors to untreated well water pumped from a depth of more than 200 feet. The water analysis is given in Table 5. The following strains of bacteria were identified from field water samples; *Pseudomonas*, *Runella*, *Acinetobacter*, and *Alcaligenes*. Data on the troughs in Phase II of the program

will not be available until 1991.

RESULTS AND DISCUSSION

The intent of the test program is to create case histories with which to illustrate the effect of welding fabrication on corrosion resistance in microbially active environments. The field results for Phase I of the program include visual, radiographic, and metallographic evaluations of welded Type 304L and 316L pipe sections as described below. As previously mentioned, field test results for the welded Alloy 904L and AL-6XN alloy troughs in Phase II of the program will not be available until 1991.

Visual Examination

The appearance, smell and feel of a biomass deposit can be useful indicators of underlying MIC.⁴¹ The troughs were examined daily for approximately the first month of the exposure. After two weeks, reddish-brown deposits/tubercles were observed over certain welds (Figure 4) and taken as an indication of iron-oxidizing bacteria.⁴² Rust-colored streaks and ring patterns surrounded pitted areas in both the Type 304L (Figure 5) and 316 troughs. The biomass was most concentrated at the bottom of the horizontal pipe.

Tubercles readily formed at the bottom of the trough on welds that had not been annealed and pickled. However, the selective tuberculation of certain welds can not be rationalized. Welds that had relatively poor fit-up were tuberculated as well as welds that were well fitted. The tubercles could be easily brushed away in order to look for pits. When this was done, new tubercles formed overnight in exactly the same location. Similar observations by others have been associated with MIC failures.⁴² Large cavernous pits formed under tubercles at welds in both Type 304L and 316L troughs (Figure 6) during the 1 year exposure to flowing well water. The height of the tubercles varied inversely with the rate of water flow. In this way, the biomass optimized shape to obtain nutrients.⁴ Samples of the mounds were taken in sterile bottles for off-site analysis, but logistical difficulties at the contacted microbiological laboratories prevented a detailed characterization of the biomass and biological residue.

The Type 304L and 316L troughs were destructively examined after one year of exposure. Small patches of rusty corrosion product discolored the as-deposited weldments and base metal areas particularly near the water line (Figure 7). Approximately a dozen small isolated areas of open, shallow pits were observed away from the weldments on the base metal of certain sections that had not been heat treated. These pits were generally very close to the water line.

None of the above visual observations applied to the annealed and pickled subassembly. There were areas of silt and other residue, but there was no evidence of discoloration or corrosion on the subassembly.

Microstructural Examination

Radiographic Examination. Each of the weldments in the Type 304L and 316L troughs

were radiographed before and after exposure. Extensive pitting was found at or adjacent to almost all of the welds in the Type 304L and 316L troughs that had not received heat treatment (Figure 8). No pits were found on the solution annealed weldments.

Metallographic Examination. Microbially influenced pitting has the morphology of a "classic" chloride pit in that a large pear-shaped void forms below a small break in the surface Figure 9. The weldment shown in Figure 9A was fabricated of Type 304L base metal using ER 308L weld filler and the pit shown in Figure 9B is of commercial annealed and pickled Type 304 exposed to a laboratory NaCl solution. The preferential etching of the weld in Figure 9A indicates that the as-welded ER 308L weld deposit behaved anodically to the Type 304 base metal.

Metallographic and SEM examinations revealed that the attack initiated with the preferential dissolution of delta-ferrite and then both phases became active (Figure 10). Cases of preferential MIC of either and both delta ferrite and austenite have been reported.⁴² This would indicate that the localized conditions under a biofilm can vary greatly. Delta-ferrite is selectively attacked in duplex weld microstructures in reducing acids⁴³ while austenite is preferentially attacked in oxidizing chloride solutions. Both phases are attacked under other conditions.⁴⁴

Ferrite Measurements. The ferrite numbers (FN's) of the welds in the Type 304L and 316L troughs were measured using a magne gage (Table 5). The FN of the ER 308L welds decreased with solution annealing, but the welds made using the E 312 filler still had FN's that were greater than 28 after annealing. Approximately equal numbers of pits occurred on all three welds, representing low, medium, and high FN values in the Type 304L and 316L sections that were not solution annealed. No pits were found on any of the solution annealed welds. Based on this result it was concluded that the MIC was too severe in the Type 304L and 316L troughs to discriminate the effect of different weld metal ferrite contents and heat inputs, as is often observed in certain chemical process environments.

Evaluation of Sensitization. Other workers have found sensitized austenitic stainless steel weldments to be susceptible to MIC.⁴⁵ In this study, "L-grade" base and filler metals were used to avoid sensitization. Samples taken from the exposed troughs were subjected to laboratory test ASTM A 262 "Standard Practices for Determining Susceptibility to Intergranular Attack in Austenitic Stainless Steels." According to the results of this test, the Type 304L and 316L base metals and the ER 308L and E 312 welds were not sensitized in either the as-welded or the heat treated conditions.

CONCLUSIONS

The following conclusions are based on a field study of welded Type 304L and 316L pipe sections exposed for one year to flowing, untreated, microbially active, well water:

1. Types 304L and 316L base metals welded with ER 308L and E 312 filler metals are susceptible to MIC in the as-welded condition. As-deposited circumferential welds are the most common sites for tubercle formation in pipe under low flow conditions. The two most likely sites for MIC in a pipe under low flow conditions are under tubercles attached to circumferential welds and under biofilms attached to

- circumferential welds at the water line. MIC sites have features that are typical of chloride pitting, specifically, large subsurface cavities with small, occluded openings.
2. Solution annealing and pickling significantly reduces the susceptibility of welded Type 304L and 316L pipe to MIC. It was not possible to determine if pickling alone would decrease susceptibility to MIC from the sample conditions tested in Phase I of this study.
 3. Preferential attack of unsensitized, circumferential ER 308L and E 312 welds in Type 304L and 316L stainless steel pipe is due to a combination of galvanic, topological and metallurgical effects. It was not possible to discriminate the relative impact of these three factors from the sample conditions tested in Phase I of this study.
 4. The MIC was too severe in the Type 304L and 316L troughs to discriminate the effect of weld metal ferrite content and heat input on the corrosion resistance of as-deposited welds.

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DISCLAIMER

Data presented are typical, and should not be construed as maximum or minimum values for specification or design. Data on any particular material may vary from those presented.

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Table 1
Pitting and Crevice Corrosion Indices

Alloy	Composition (wt%)			PRE _N ¹	CCCT ² (°F/ °C)	CPT ³ (°F/ °C)	CPT ⁴ (°F/ °C)
	Cr	Mo	N				
Type 304L	18.0	—	0.06	19.8	<27.5 (<-2.5)		
Type 316L	16.5	2.1	0.05	24.9	27.5 (-2.5)	59 (15.0)	
Alloy 904L	20.5	4.5	0.05	36.9	68.0 (20.0)	104 (40.0)	113 (45)
AL-6XN®	20.5	6.3	0.23	47.9	110 (43.0)	177 (80.5)	172 (78)

¹ Pitting Resistance Equivalent (PRE_N) = Cr + 3.3 Mo + 30N.
² Critical Crevice Corrosion Temperature (CCCT) based on ASTM G-48B (6% FeCl₃ solution for 72 hr with crevices).
³ Critical Pitting Temperature (CPT) based on ASTM G-48A (6% FeCl₃ solution for 72 hr).
⁴ Critical Pitting Temperature (CPT) based on ASTM G-48A practice but with a 4% NaCl + 1% Fe₂(SO₄)₃ + 0.01 M HCl solution.

Table 2
Partial Chemical Compositions for Examined Base and Filler Metals

AISI Type or Tradename		UNS No.	Composition (wt%)				
			C	Mn	Cr	Ni	Mo
Base Metals:							
304L	S30403	0.019	1.40	18.20	9.25	0.26	Cu=0.036
316L	S31603	0.024	1.78	17.17	11.27	2.17	N=0.04, Cu=0.18
317L	S31703	0.025	1.65	18.38	13.30	3.31	N=0.060
904L	N08904	0.020	1.89	20.45	24.90	4.70	Cu=1.55, N=0.030
AL-6XN®	N08367	0.020	1.63	20.68	24.73	6.30	N=0.21, Cu=0.18
Filler Metals:							
ER 308L (low)	W30848	0.018	1.98	20.08	10.17	0.26	Si=0.28
ER 308L (high)	W30848	0.016	1.79	20.46	10.6	0.22	Si=0.54
E 312	W31310	0.012	1.75	29.94	8.71	0.29	Si=0.39
625	N06625	0.02	0.21	21.15	60	8.79	Ta+Nb=3.64
276	N10276	0.004	0.45	15.69	57	15.58	W=3.3, Co=1.79
Hastelloy [¥]							
C-22	N06022	0.002	0.3	21.5	60	14	W=3.3, V=0.15

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¥ Hastelloy is a registered trademark of Haynes International, Inc.

Table 3
Typical Physical Properties of Austenitic Stainless Steels

Property	Typical values for AISI 300 series stainless steels	Typical values for AL-6XN® alloy
Ult. tensile strength	85,000 - 95,000 psi	108,000 psi
Yield strength	30,000 - 40,000 psi	53,000 psi
Elongation (in 2 in.)	55 - 60%	47%
Reduction in area	60 - 70%	65%
Hardness	135 - 180 Brinell	185 Brinell
Density	0.29 lb/in ³	0.29 lb/in ³
Melting point range	2550 - 2590°F	2410-2550°F
Approx. scaling temp. (avg., in air)	1650°F	1885°F

Table 4
Test Specimens for MIC Testing

	Base Metal AISI Type	Pipe O.D. (in.)	Pipe Schdl.	Pipe Wall (in.)	Filler Metal	Filler Metal Form	Weld FN	Final Condition
Phase I:								
1	304L	6	10	0.134	308L	Wire	6.5	AW
2	304L	6	10	0.134	308L	Wire	8.1	AW
3	304L	6	10	0.134	312	Wire	28*	AW
4	304L	6	10	0.134	308L	Wire	0	A&P
5	304L	6	10	0.134	308L	Wire	1.4	A&P
6	304L	6	10	0.134	312	Wire	28*	A&P
7	316L	6	10	0.134	308L	Wire	3.6	AW
8	316L	6	10	0.134	308L	Wire	8.3	AW
9	316L	6	10	0.134	312	Wire	28*	AW
10	316L	6	10	0.134	308L	Wire	0.3	A&P
11	316L	6	10	0.134	308L	Wire	2.0	A&P
12	316L	6	10	0.134	312	Wire	28*	A&P
Phase II:								
13	904L	4	40	0.237	625	Insert	0	AW
14	AL-6XN®	4	40	0.225	625	Wire	0	AW
15	AL-6XN	4	40	0.225	276	Wire	0	AW
16	AL-6XN	4	40	0.225	C-22	Wire	0	AW
17	AL-6XN	4	40	0.225	625	Insert	0	AW
18	AL-6XN	4	40	0.225	276	Insert	0	AW
19	AL-6XN	4	40	0.225	C-22	Insert	0	AW
20	AL-6XN	4	40	0.225	625	Insert	0	A&P
21	AL-6XN	4	40	0.225	276	Insert	0	A&P
22	AL-6XN	4	40	0.225	C-22	Insert	0	A&P
* Upper measuring limit of Magne Gage								
Key: AW - As-Welded; A&P - Annealed and Pickled; FN - Ferrite Number.								

Table 5
Water Analysis

	#1 (mg/l)	#2 (mg/l)
Arsenic	0.022	0.031
Barium	<0.5	<0.5
Cadmium	<0.005	<0.005
Chromium	0.013	0.023
Fluoride	6.9	9.5
Lead	<0.02	<0.02
Mercury	<0.001	<0.001
Nitrates	2.0	3.0
Selenium	<0.005	<0.005
Silver	<0.02	<0.02
Alkalinity	144.	178.
Calcium	13.	7.9
Chloride	226	126
Copper	<0.05	<0.05
Hardness	58	34
Iron	<0.1	<0.1
Magnesium	6.3	3.6
Manganese	<0.05	<0.05
pH	8.1	8.1
Sodium	250.	206
Sulfate	98.	87.
TDS	740.	580.
Zinc	<0.05	<0.05

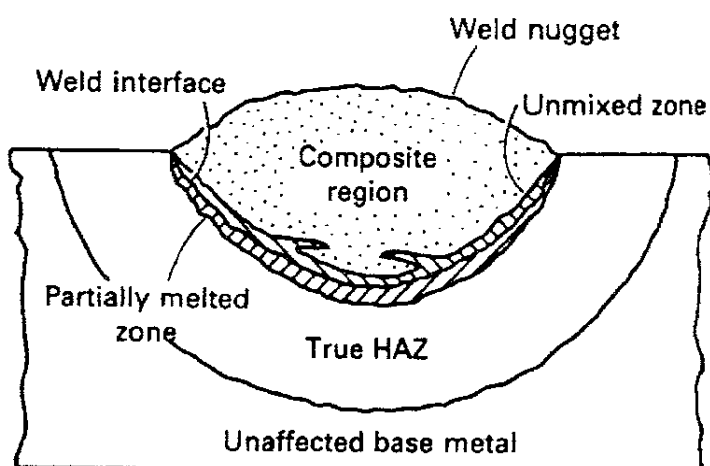


Figure 1—Schematic illustration showing the regions of a heterogeneous weld. ²⁷

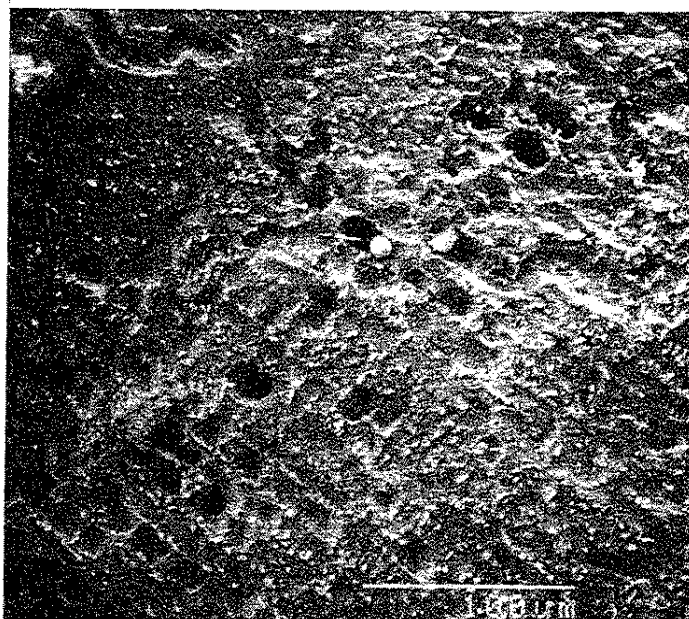


Figure 2—Localized corrosion at inter-dendritic regions of a ER 308L weld in a Type 304L pipe exposed for 1 year to flowing well water.

Figure 3—"MIC troughs" consisting of Type 304L pipe with nine circumferential welds.

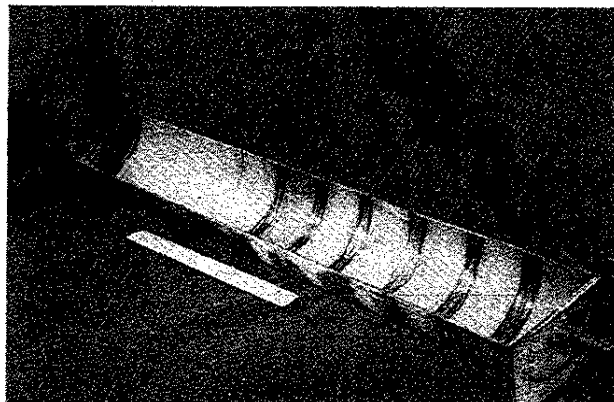




Figure 4—Tubercle formed Type 304L pipe after two weeks of exposure to flowing well water.

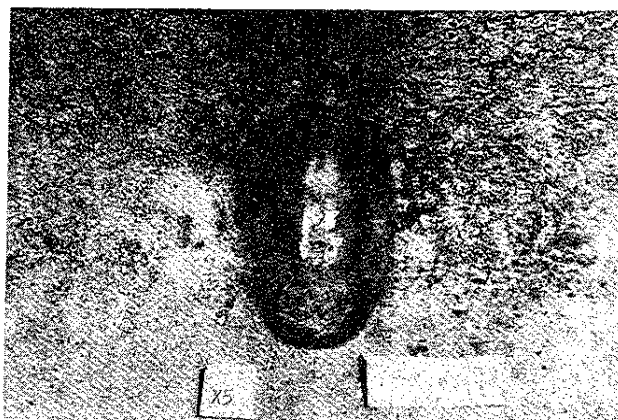
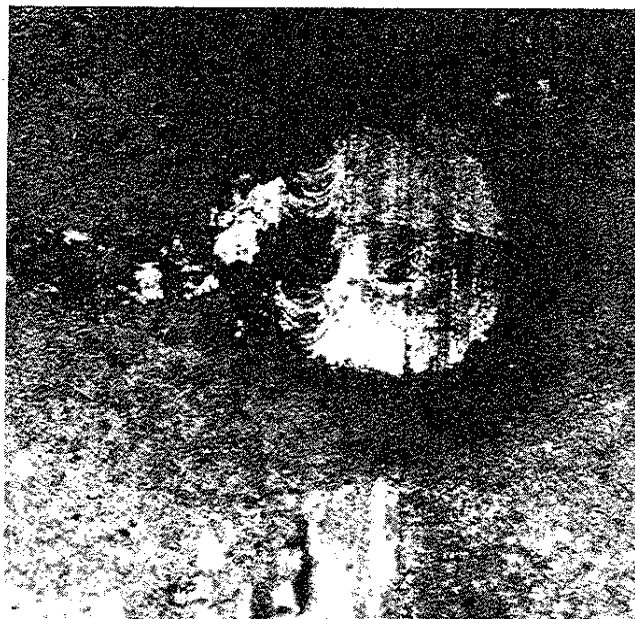


Figure 5—Rust-colored streaks and ring patterns surrounding a pitted area in a Type 304L pipe exposed for 1 year to flowing well water.



A



B

Figure 6—Large cavernous pits formed under tubercles at welds in both Type 304L (A) and Type 316L (B) pipes. The pipes had been exposed for 1 year to flowing well water.



Figure 7—Corroded as-deposited weldments and base metal areas near the water line of Type 304L pipe exposed for 1 year to flowing well water.

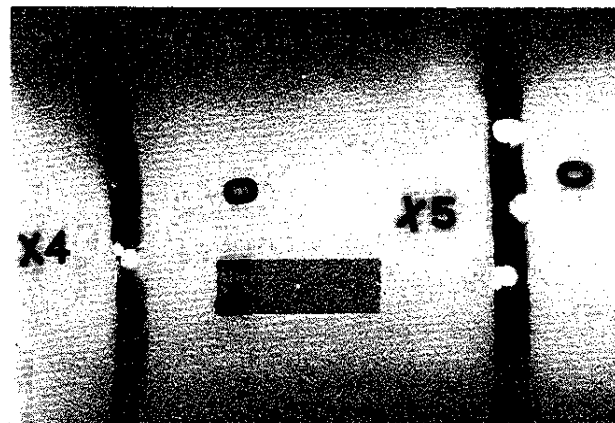
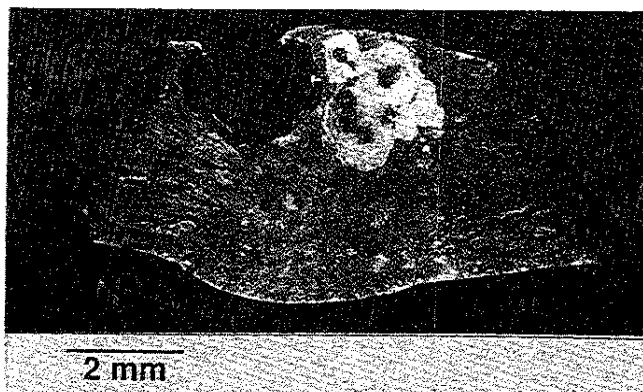
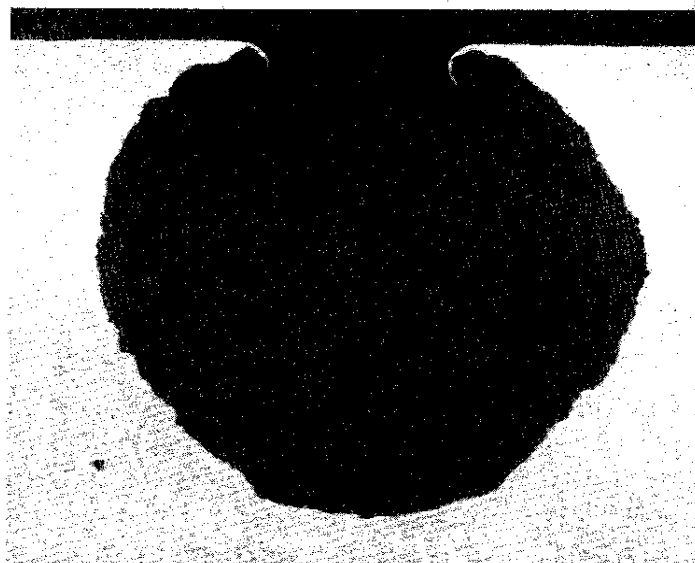


Figure 8—Radiograph of Type 304L pipe exposed for 1 year to flowing well water showing extensive pitting at and adjacent to ER 308L weld.



A



B

Figure 9—Comparison of MIC and chloride pit morphologies: The pit in "A" occurred in a Type 304L pipe welded with ER 308L filler and the pit in "B" occurred in commercially produced Type 304 strip exposed to a laboratory NaCl solution. (Electrolytic 10% oxalic acid etch).

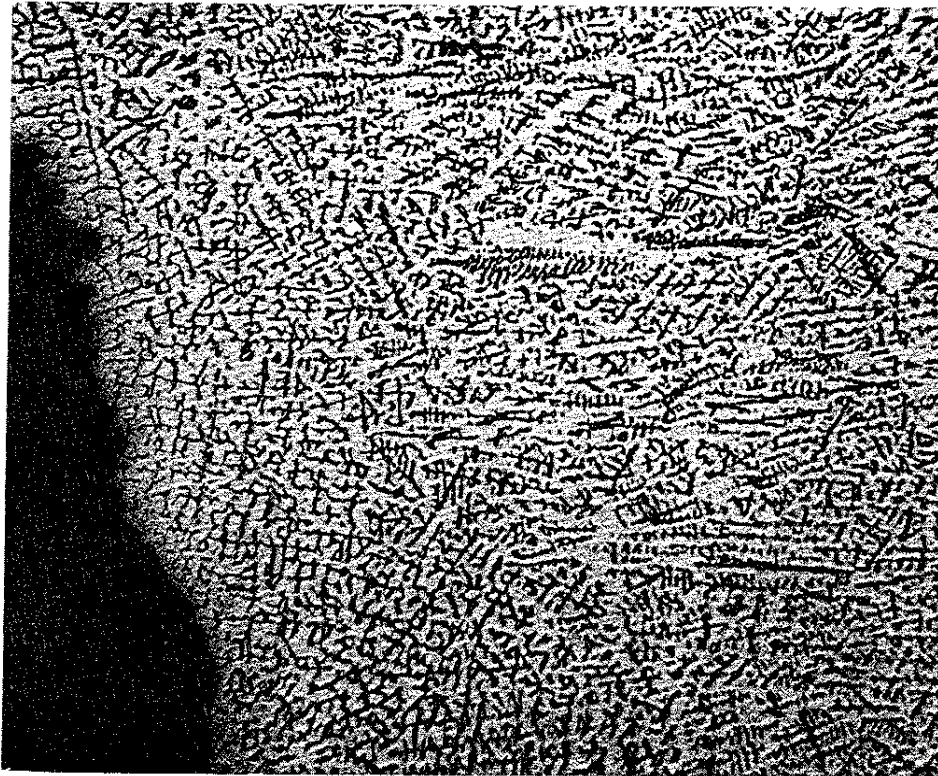


Figure 10—Photomicrograph showing preferential attack of ferrite in ER 308L weld. (Electrolytic 10% oxalic acid etch).