Technical Note: Stress Corrosion Cracking in Duplex Stainless Steel Weldments

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Background

The extensive use of welded austenitic stainless steels by the power and chemical industries has caused a considerable interest in duplex stainless steel weldments. As a result, substantial work has been performed to determine the influence of ferrite on a variety of duplex stainless steel weldment properties. The well-known studies of Borland, Hull, and numerous others have shown the beneficial effects that small amounts of ferrite can have on improving the hot-cracking and microfissuring resistance of weldments in austenitic stainless steels.

Despite the wide application of duplex stainless steel weld metals in environments conducive to stress-corrosion cracking, relatively few studies have been performed to determine the stress-corrosion cracking characteristics of duplex weldments. Investigations by Fontana *et al.*[1] in the early 1960's indicated that cast duplex alloys are more resistant to stress-corrosion cracking than single-phase austenitic alloys. Unfortunately, the results of these studies have led several people to believe that duplex weldments exhibit higher stress-corrosion cracking resistance than wholly austenitic weldments.

Actually, the stress-corrosion cracking characteristics of duplex weldments may be considerably different than those of cast and wrought structures of the same chemical composition. This difference results primarily from the much faster cooling rates encountered in weldments as compared to cast and wrought structures. These faster cooling rates lead to much higher degrees of microsegregation and finer ferrite distributions, both of which play significant roles in determining stress-corrosion cracking susceptibility.

Studies completed at Rensselaer Polytechnic Institute by Sherman *et al.*[2] and Duquette and Stalder[3] have shown that both the stress-corrosion cracking susceptibility and the failure mode of a duplex weldment may differ considerably from the susceptibility and failure mode of an annealed stainless steel with the same chemical composition. Their constant-strain, constant-stress, and constant-extension-rate stress-corrosion cracking tests performed on welded and unwelded Type 304L stainless steel sheet specimens in boiling $MgCl_2$ showed that stress corrosion in duplex weld metal occurs preferentially along the ferrite-austenite interfaces, while cracking in the annealed base metal occurs transgranularly through the austenite. This interphase mode of cracking was attributed to the large

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Table 1—Ferrite Numbers and Chemical Compositions of Base and Weld Metals Employed in This Investigation

Material designation	Ferrite number*	Chemical compositions, %[b] C	Cr	Ni	Si	Mn	P	S	Co	Mo	Cu
BM1 (Type 304)	0	0.055	18.28	8.55	0.61	1.55	0.03	0.015	0.16	0.18	0.12
BM2 (Type 304L)	0	0.027	18.55	9.61	0.59	1.55	0.03	0.005	0.10	0.18	0.12
WM1 (310/304L)	0	0.08	24.1	17.3	0.5	1.6	0.02	0.003	0.1	0.2	0.1
WM2 (310/304L)	1	0.06	22.5	15.1	0.5	1.6	0.02	0.004	0.1	0.2	0.1
WM3 (310/304L)	3	0.04	20.1	11.8	0.5	1.6	0.03	0.004	0.1	0.2	0.1
WM4 (Type 304)	6	0.05	18.3	8.5	0.6	1.5	0.03	0.015	0.1	0.2	0.1
WM5 (312/304L)	11	0.04	20.2	9.5	0.6	1.5	0.03	0.006	0.1	0.2	0.1
WM6 (312/304L)	16	0.04	21.8	9.4	0.6	1.6	0.03	0.007	0.1	0.2	0.1
WM7 (312/304L)	24	0.06	22.8	9.2	0.6	1.6	0.03	0.008	0.1	0.2	0.1

[a]As measured by an Aminco-Brenner Magne-Gage.
[b]Analysis of weldments calculated from dilution measurements.

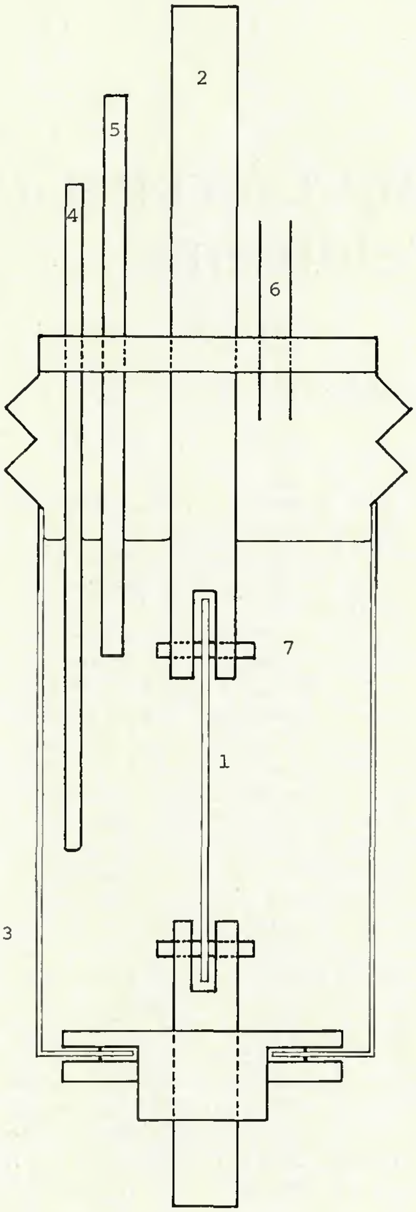

Fig. 1—Test cell: 1—specimen; 2—zirconium grips; 3—glass cell; 4—thermometer; 5—argon bubbler tube; 6—argon exit tube; 7—epoxy coated titanium pins

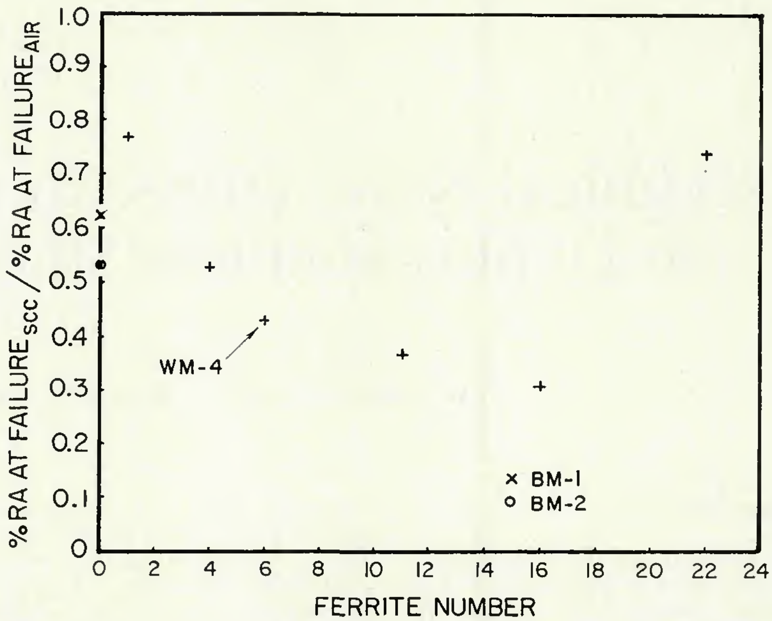

Fig. 2—Percent reduction in area$_{SCC}$/percent reduction in area$_{air}$ vs. Ferrite Number for base and all-weld-metal gage section CER test specimens

compositional differences which exist between the adjacent austenite and ferrite phases.

In order to understand more fully the influence of ferrite on the stress-corrosion cracking characteristics of duplex weldments, several aspects of the phenomenon must be investigated. The effects of ferrite content and morphology in both the weld fusion zone and the weld heat-affected zone must be determined. In addition, the importance of environmental effects, such as solution composition, concentration, and temperature, must be understood.

Experimental

Constant-extension-rate (CER) tensile tests were performed on welded stainless steel sheet specimens with ferrite contents of Ferrite Number 0, 1, 3, 6, 11, 16, and 24. These room-temperature tests were run in deaerated, 1*N* HCl at an extension rate of 0.0002 ipm (0.005 mm/min.) (equivalent to an initial strain rate of 1.48×10^{-6} s^{-1}) and in air at an extension rate of 0.002 ipm (0.05 mm/min.) (equivalent to an initial strain rate of 1.48×10^{-5} s^{-1}). Specimens contained either an all-weld-metal gage section or a transverse weld through the center of the gage section perpendicular to the tensile axis.

Weld metals were fabricated using a procedure which involved producing a GMAW-P weldment with Type 310 or 312 filler metal on a Type 304L base metal, removing the weld reinforcement, and producing an autogenous GTAW weldment which totally engulfed the GMAW-P weld fusion zone. By varying the size of the GMAW-P weldment and maintaining constant GTAW welding parameters, a range of ferrite levels from zero to over 40 vol-% could be accurately and reproducibly obtained. Table 1 provides chemical compositions of the weld metals tested in this investigation.

Prior to testing, all specimens were wet ground with 600 SiC paper, washed with distilled water, and desiccated for 24 h. In addition, all but the gage section of all-weld-metal gage section specimens was masked with Microshield to eliminate base metal-weld metal galvanic interactions.

The test cell employed throughout the investigation is illustrated in Fig. 1. Deaeration was achieved by bubbling high-purity argon continuously through the solution.

Analysis of fractured specimens was performed using both scanning electron and light microscopy metallographic techniques.

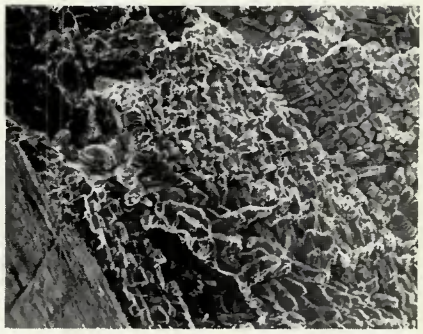

Fig. 3—Scanning electron microscope micrograph of the fracture surface of an all-weld-metal FN-6 specimen, ×500 (reduced 52% on reproduction)

Results and Discussion

Figure 2 illustrates the effects of ferrite content on duplex weldment stress-corrosion cracking resistance. It does so by comparing the reductions in area at failure of all-weld-metal specimens tested in solution to those of specimens tested in air. The greatest stress-corrosion cracking susceptibility appears to be in the FN-6 to FN-20 range, where continuous networks of vermicular ferrite provide easy paths for stress-corrosion cracking.

Scanning electron micrographs of fracture surfaces of specimens in the FN-6 to FN-20 range clearly showed that stress-corrosion cracking occurred by preferential dissolution of the ferrite or austenite-ferrite interphase regions—Fig. 3. At ferrite contents below about FN-6 the discontinuous ferrite distributions prevented stress-

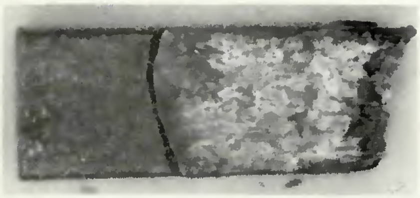

Fig. 4—Preferential SCC attack in the heat-affected zone of a weld with totally austenitic weld (right) and base (left) metals, ×9 (reduced 38% on reproduction)

corrosion crack growth exclusively by ferrite or interphase dissolution. Instead, cracks were sometimes forced to propagate transgranularly or in a ductile manner through the austenite.

This mixed mode of cracking resulted in slowed crack growth. When the ferrite level exceeded approximately FN-20, the vermicular ferrite structure evolved into a structure which consisted of large ferrite grains surrounded by austenite. In these high-ferrite specimens, dissolution of the ferrite or interphase regions was stifled by the continuous austenite networks.

Test results for annealed Type 304 and 304L base metals are also included in Fig. 2 for comparative purposes. A considerable difference in stress-corrosion cracking susceptibility can be observed between the annealed Type 304 base metal (BM-1) and a duplex weld metal of the same chemical composition (WM-4). Stress-corrosion cracking in these base metals occurred transgranularly, with considerable subsurface crack dissolution.

The results of constant-extension-rate stress-corrosion cracking tests on specimens with transverse weldments indicated that stress-corrosion cracking may occur preferentially in the weld heat-affected zone. Stainless steel weldment solidification and morphology studies at Rensselaer Polytechnic Institute have shown that ferrite may be formed in the weld heat-affected zone.[4] During the welding operation the initially wholly austenitic base metal surrounding the molten weld pool is rapidly heated to temperatures which partially transform the austenite into ferrite.

The regions of the heat-affected zone, which first transform into ferrite on heating, are usually solute bands (oriented parallel to the plate or sheet rolling direction), where ferrite-stabilizing elements such as Cr, Mo, Si, and Cb are highly concentrated or where austenite-stabilizing elements such as

Fig. 5—Preferential SCC attack in the heat-affected zone of a weld with totally austenitic weld (right) and base (left) metals. Mixed acid etch, ×150 (reduced 45% on reproduction)

Ni, Mn, C, and N are in low concentration. In the partially melted region adjacent to the molten weld pool, austenite grain boundaries actually liquate, and upon cooling often solidify partially as ferrite.

Electron microprobe studies have found that at high temperatures, ferrite-stabilizing elements exhibit a greater solubility in the ferrite than in the austenite and consequently partition to the ferrite. Likewise, austenite-stabilizing elements are more soluble in austenite than in ferrite and tend to partition to the austenite. This alloying-element partitioning, coupled with the extremely fast cooling rates associated with the weld heat-affected zone, can prevent the ferrite regions from transforming entirely back to austenite on cooling and result in the retention of some ferrite down to room temperature.

Figures 4 and 5 illustrate the considerable heat-affected-zone attack in a specimen which contained totally austenitic base and weld metals. Scanning electron microscope micrographs showed that stress-corrosion cracking and subsequent specimen failure occurred by dissolution of the nearly continuous ferrite networks in the weld heat-affected zone—Fig. 6.

It is important to note that unstressed specimens exhibited virtually no preferential attack. Thus, the stress-corrosion cracking susceptibility of a stainless steel weldment may not depend exclusively on the resistance of the weld metal, but rather on the resistance of the weld heat-affected zone.

Conclusion

Ferrite content and distribution have

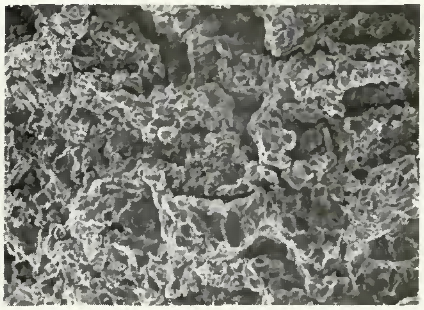

Fig. 6—Scanning electron microscope micrograph of the fracture surface of a transverse weld specimen with totally austenitic base and weld metals, ×575 (reduced 54% on reproduction)

been found to be significant in determining both the stress-corrosion cracking susceptibility and the failure mode of duplex stainless steel weldments. The most susceptible duplex weld metals appear to be those which exhibit continuous or nearly continuous ferrite networks. Whenever possible, stress-corrosion cracking occurs by preferential dissolution of the ferrite or austenite-ferrite interphase regions.

The duplex heat-affected zone structure formed during the welding operation appears to be particularly susceptible to stress-corrosion cracking. As a result, the resistance of the weld metal may be of secondary importance, with weldment susceptibility being determined primarily by the resistance of the weld heat-affected zone.

Acknowledgment

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