WELDING RESEARCH

SUPPLEMENT TO THE WELDING JOURNAL, JULY 1977

Sponsored by the American Welding Society and the Welding Research Council

Cause and Prevention of 12% Chromium Steel Fillet Weld Cracks

Cracking in Type 410 stainless steel submerged arc welds can be eliminated by using Type 410-Ni filler metal with no changes in welding technique or weld bead contour

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Introduction

The 12% chromium martensitic stainless steels possess properties which make them desirable for many engineering applications. They can be heat treated to tensile strengths above 100 ksi (689 MPa) and they maintain good strength up to about 1100 F (600 C). In addition, they exhibit good erosion, corrosion and scaling resistance. While the martensitic stainless steels are considered among the more difficult materials to weld, they can be successfully welded with careful control of preheat temperature and postweld heat treatment. Martensitic stainless steels with carbon contents above 0.25% are very difficult to weld, and industrial applications involving the welding of these steels are limited.

Grades such as Type 410, Type 403 or Type 410 Cb stainless steels which contain less than 0.15% carbon are commonly joined by a wide variety of welding processes including resistance welding, arc welding and electroslag welding. When these steels are used as components in commercial or industrial machinery, fabrication is usually accomplished by one of the arc welding processes including shielded metal arc, gas tungsten arc and submerged arc welding.

Shielded metal arc welding is used in many applications. However, where practical, submerged arc welding offers the advantages of increased deposition rates and the ability to produce smooth, continuous weld deposits. Another attribute of the submerged arc process is its ability to produce concave fillet welds. A concave contour is desirable for many applications to minimize stress concentrations or improve the surface finish of the fillet weld.

Welds with strengths equivalent to the base metal can be produced by using a filler metal whose chemical composition is similar to the base metal. These filler metals are commonly available for the arc welding processes. A typical welding procedure used with these filler metals requires the weld area to be preheated to temperatures between 400 and 600 F (200 and 300 C). These temperatures are maintained during the entire welding operation and usually until postweld heat treatments are begun.

Welding on annealed base material and then heat treating the entire weldment will produce the most homogeneous structure and optimum mechanical properties. However, because of the difficulties of quenching and tempering complex structures, a common practice is to weld fully heat treated component parts.

The martensitic stainless steels, particularly Type 410 Cb, have low M_f temperatures. Therefore, they should be cooled below their M_f temperature prior to stress relief to ensure complete transformation of the HAZ to martensite. Finally, a postweld stress relief treatment is performed. This stress relief consists of heating the weldment to a temperature just below (typically 50 F (28 C)) the tempering temperature of the component parts, holding for 1 hour per inch of section (minimum) and cooling slowly in a furnace.

Despite the use of careful controls

Paper presented at the 58th AWS Annual Meeting held in Philadelphia, Pennsylvania, during April 25-29, 1977.

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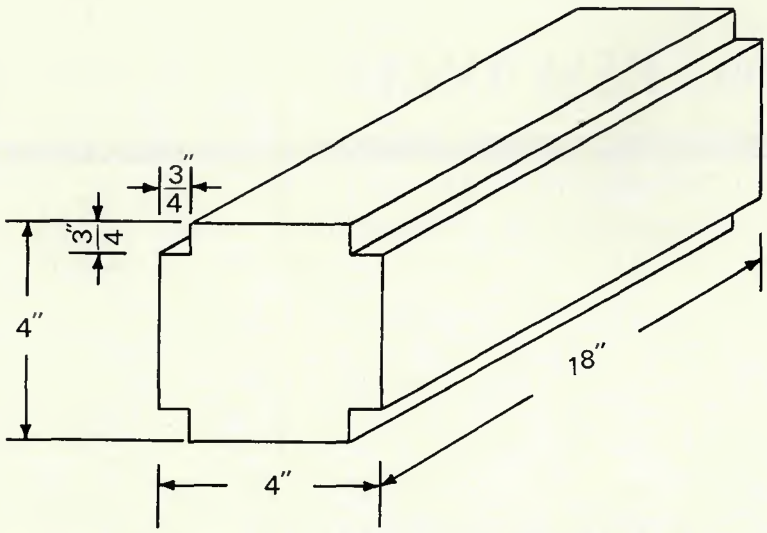

Fig. 1—Cruciform test specimen

as well as recommended procedures and proper temperatures for preheat and postweld heat treatment, cracking can occur in welds during fabrication of 12% chromium stainless steels.

Concave, single pass fillet welds seem particularly vulnerable. Intermittent center bead cracks from 0.062 to 0.5 in. (1.57 to 12.7 mm) long have occurred in restrained, single pass, submerged arc fillet welds produced with Type 410 filler metal on Type 403, Type 410 and Type 410 Cb steels using proper procedures.

There is a great deal of information available on the causes of weld metal cracking in carbon steels, alloy steels and austenitic stainless steels. However, the literature offers little guidance concerning martensitic stainless steels other than to control sources of hydrogen, reduce restraint, utilize proper preheat and postweld heat treatment or use austenitic stainless steel filler metal. None of these measures appeared to offer the solution to the observed fillet weld cracking. Therefore, an investigation was conducted to study the variables involved in welding martensitic stainless steels, to isolate the cause of center bead cracking and to develop a procedure which would produce sound welds.

Experimental Procedure

Selection of a Laboratory Test Specimen

The first step during this investigation was the selection of a test specimen which would produce center bead weld cracking. Tests showed that cracking could not be produced by double fillet welds deposited on T joints between two 0.5 in. (12.7 mm) thick Type 410 stainless steel plates. A previous laboratory investigation had successfully produced center bead weld cracking on alloy steels using the cruciform specimen shown in Fig. 1. A given cruciform bar could be used more than once for weld evaluations

Table 1—Welding Parameters for Laboratory Cruciform Test Welds

Test weld[a]	Electrode	Flux #	Current polarity	Amperage, A	Voltage, V	Travel speed, ipm	(mm/min.)	Weld contour	Results
A-1	Type 410-B	1	DCRP	200	30	10	(254)	Concave	0.062-0.125 in. (1.5-3 mm) cracks
A-2	Type 410-B	1 (not baked)	DCRP	200	30	10	(254)	Concave	0.062-0.125 in. (1.5-3 mm) cracks
A-3	Type 410-A	1	DCRP	200	30	10	(254)	Concave	0.062-0.125 in. (1.5-3 mm) cracks
B-3	Type 410-A	1	DCRP	200	30	10	(254)	Concave	0.062 in. (1.5 mm) cracks
C-1	Type 410-A	1	DCSP	200	30	10	(254)	Flat	0.062-0.250 in. (1.5-6 mm) cracks
C-4	Type 410-A	1	DCSP	200	26	10	(254)	Convex	No cracks
D-4	Type 410-A	1	DCRP	250	25	14	(355)	Convex	0.062 in. (1.5 mm) cracks
E-1	Type 410-A	1	DCRP	200	24	20	(508)	Flat	0.062 in. (1.5 mm) cracks
E-2	Type 410-A	3	DCRP	200	30	10	(254)	Concave	0.062 in. (1.5 mm) cracks
E-3	Type 410-A	2	DCRP	200	30	10	(254)	Concave	0.062 in. (1.5 mm) cracks
E-4	Type 410-A	4	DCRP	200	30	10	(254)	Concave	0.125-0.188 in. (3-5 mm) cracks
G-3	AM-363	3	DCRP	180	32	14	(344)	Concave	No cracks
G-4	AM-363	1	DCRP	180	32	14	(355)	Concave	No cracks
H-4	E-410-16	None	DCRP	190	—	12	(305)	Flat	No cracks
M-1 thru M-4	AM-363	1	DCRP	200	30	14	(355)	Concave	No cracks
N-1 thru N-4	AM-363	4	DCRP	200	30	14	(355)	Concave	No cracks
P-1 thru P-4	E-410-16	None	DCRP	230	—	—		Concave	0.125-0.250 in. (3-6 mm) cracks
0-1 thru 0-4	AM-363	1	DCRP	200	30	14	(355)	Concave	No cracks

(a)Minimum 400 F (204 C) preheat temperature except 550 F (288 C) for test weld 8-3

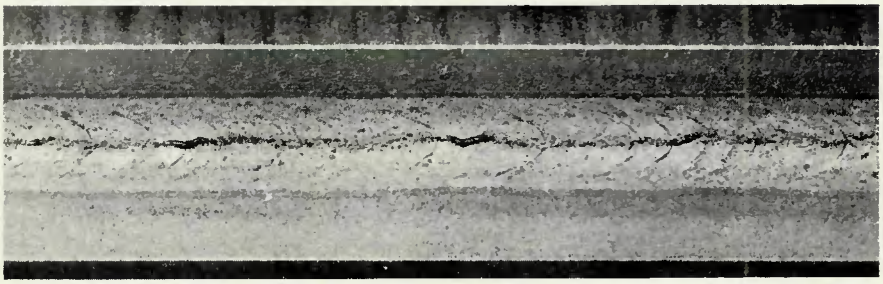

Fig. 2—Typical center bead cracking of Type 410 stainless steel fillet weld as shown by magnetic particle inspection. ×1

Fig. 3—Macrograph of a submerged arc weld cross-section showing bead contour and crack pattern. Etchant: $FeCl_3$. ×6 (reduced 28% on reproduction)

by stress relieving the welded bar and machining away the fillet welds and approximately 0.125 in. (3 mm) of base metal.

The cruciform test specimen shown in Fig. 1 was machined from Type 410 stainless steel bar stock. Test welds were made on the specimen using the submerged arc process, Type 410 stainless steel electrode, a neutral flux and the welding parameters normally used to produce concave fillet welds on martensitic stainless steels. The welding conditions were identical to test weld A-3, shown in Table 1. The desired type of center bead cracking occurred in these test welds. Figure 2 shows the size and distribution of typical cracks. Figure 3 is a cross section through a concave fillet weld containing extensive center bead cracking.

The ability to produce the desired cracking conditions indicated that this cruciform test specimen could be used to evaluate the effects of welding parameters, types of electrodes, and fluxes on weld cracking. If a technique could be found which produced crack-free welds on the cruciform specimen, then the technique would be expected to produce crack-free welds in other applications.

Test Welding

More than 60 test welds were deposited on cruciform specimens to determine which welding variables influenced center bead weld cracking. Table 1 summarizes typical test welds. Not all welds made during the study are shown. Table 1 contains only those test welds which are pertinent to this discussion. Table 2 lists the chemical compositions of Type 410 and Type 410 Cb stainless steels used for the cruciform specimens. Weld A-3 represents the baseline welding procedure known to produce center bead cracking in concave fillet welds. As shown in Table 1, this procedure utilizes 400 F (204 C) minimum preheat, Type 410 electrode (manufacturer A) and neutral flux #1.

In order to determine if hydrogen or excessive moisture in the welding flux caused the cracking, a weld was made using flux taken directly from an open bag which had been sitting in the laboratory atmosphere for several weeks (Weld A-2). Another weld using identical parameters and welding materials was also made, except the flux was dried by heating it to 800 F (427 C) for 10 h and then holding it in a heated oven at 250 F (121 C) prior to use (Weld A-1). All subsequent welds during this investigation used fluxes which had been baked and stored in heated ovens prior to use.

The next variable considered was preheat temperature. Several welds similar to B-3 were made at 550 F (288 C) preheat temperature.

Welds C-1 through E-1 were produced to determine the effects of weld bead contour on cracking. All of these welds were made using the same electrode (Type 410-A), neutral flux #1 and 400 F (204 C) minimum preheat temperature. Welding current, polarity, voltage, and travel speed were changed to alter the weld bead contour and penetration.

Test welds E-2, E-3 and E-4 evaluated the effects of welding fluxes on weld chemistry and cracking susceptibility. Each weld was made using electrode Type 410-A and identical welding parameters, but with a different

Table 2—Chemical Compositions and Chromium Equivalents of Base Materials, Electrodes and Weld Deposits

	Chemical composition, wt-%									
Description of material	C	Mn	P	S	Si	Ni	Cr	Mo	Other	Chromium equivalent
Type 410 cruciform base metal	.088	.43	.022	.017	.24	.42	11.74	.39	–	8.99
Type 410 Cb cruciform base metal	.14	.47	.014	.005	.35	–	11.94	–	.10 Cb	7.67
Type 410 electrode B	.13	.49	.016	.008	.40	.30	13.17	.30	–	9.43
Type 410 electrode A	.09	.42	.010	.015	.38	.03	13.09	.37	–	12.09
Type AM-363 electrode	.021	.34	.020	.006	.03	3.83	11.87	.18	.29 Ti	2.05
E-410-16 (undiluted deposit)	.08	.91	.028	.020	.40	.21	14.20	.37	–	12.18
Test weld A-1	.12	.72	.018	.015	.80	.35	11.57	.23	–	9.41
E-410 Ni-16 (undiluted deposit)	.04	.45	.020	.016	.30	3.90	13.00	.40	–	2.04
Test weld A-3	.086	.73	.016	–	.61	.32	11.49	.40	–	10.48
Test weld E-2	.073	.64	.022	.017	.86	.24	12.76	.39	–	13.95
Test weld E-3	.09	.67	–	–	–	.28	11.76	.25	–	13.13
Test weld E-4	.085	.92	.027	.014	.47	.50	13.38	.39	–	10.72
Test weld G-3	.055	.90	.020	.016	.81	2.52	12.29	.43	–	6.75
Test weld H-4	.05	.73	.019	–	.28	.23	14.02	.43	–	13.13
Test weld M-1	.10	.74	.023	.014	.50	2.05	11.72	.35	–	4.16
Test weld N-1	.13	.83	.031	.013	.54	2.58	12.55	.32	–	2.11
Test weld P-4	.05	.73	.019	–	.28	.23	14.02	.43	–	13.13

welding flux. Four welding fluxes representing two different flux types and three separate manufacturers were evaluated. Fluxes #1 and #2 were neutral fluxes used for welding carbon, alloy and martensitic stainless steels. Fluxes #3 and #4 were slightly alloyed fluxes produced by two different manufacturers specifically for welding stainless steels.

The effects of electrode chemistry were evaluated by comparing test welds A-1, A-3 and G-4. These welds were all made with welding flux #1 and with the baseline parameters which produced a concave weld contour; however, a different electrode wire was used for each. Two electrodes produced to Type 410 filler metal specifications by two different manufacturers are designated Type 410-A and Type 410-B. The chemical compositions of these wires are shown in Table 2. The third electrode evaluated was a 12% chromium, 4% nickel, molybdenum electrode wire designated AM-363 or Type 410-Ni; the normal chemical composition for AM-363 is shown in Table 2.

Cruciform tests were also welded with the shielded metal arc process and E-410-16 as well as E-410-Ni-16 electrodes. Welding parameters and techniques were varied to produce both convex and concave beads to represent the wide variety of possible bead shapes.

Next, a series of cruciform test bars were welded to double-check previous results and to verify which methods actually eliminated cracking. Four fillet welds were made on each test bar (I through N) using a given welding technique. The cruciforms were preheated, welded, cooled to 350 F (177 C), stress relieved at 1100 F (593 C) and furnace-cooled. An additional cruciform "O" was machined from Type 410 Cb material and welded to determine if welding procedures which were successful on Type 410 stainless steel would also be successful on Type 410 Cb.

After each cruciform was welded and heat treated, it was inspected using wet magnetic particle methods to reveal cracks. After this inspection, selected welds were sectioned and prepared for metallurgical examination. Samples were also taken for chemical analysis so that weld chemistry could be correlated with metallurgical structure. Evaluation of the cruciform tests indicated that the procedures used for tests "M" and "N" were successful in preventing fillet weld cracking.

Two procedure qualification test plates consisting of 0.5 in. (12.7 mm) thick Type 403 stainless steel were welded using the same welding parameters used for cruciforms "M" and "N." After welding and stress relief, these test plates were sectioned and tested in accordance with the requirements of ASME Boiler and Pressure Vessel Code, Section IX.

Fig. 4—Test weld A-3 showing crack sensitive concave weld contour. Width/depth = 2.5; dilution = 48.6%. Etchant: $FeCl_3$. ×6 (reduced 24% on reproduction)

Fig. 5—Test weld D-4 showing a very crack sensitive flat contour. Width/depth = 1.32; dilution = 52.4%. Etchant: $FeCl_3$. ×2.75

Fig. 6—Test weld C-4 showing a crack resistant convex contour. Width/depth = 1.22; dilution = 38.3%. Etchant: $FeCl_3$. Actual size

Discussion

The welding conditions shown in Table 1 for test weld A-3 formed the baseline submerged arc procedure for this entire study. These welding conditions produced a smooth, concave fillet which can be desirable for certain applications where martensitic stainless steels are used. The preheat temperature range of 400–500 F (204–260 C) and method of postweld heat treatment are well within normal guidelines for welding martensitic stainless steels. In addition, experience has shown this concave weld deposit to be the most sensitive to the type of center bead cracking under study. If a procedure could successfully produce concave welds on the laboratory cruciform specimen, then those procedures should be equally successful in a wide variety of less crack sensitive situations.

Test weld H-4, shown in Table 1, was the baseline for SMA welding. This test utilized E-410-16 electrodes and the same preheat and postweld heat treatments used for submerged arc welding.

The approach used to solve the center bead cracking problem was to make a series of test welds to isolate those variables which influenced weld cracking.

Influence of Flux Condition and Preheat Temperature

Hydrogen induced cracking is always a possibility when welding a high alloy steel. Weld A-1 was made with flux which was baked at 800 F (427 C) to remove all possible moisture. Cracking found in A-1 was similar to cracking found in weld A-2 made with flux which had not been baked. Preheat temperature was found to have no significant influence on cracking when weld B-3 (550 F (288 C) preheat) cracked as did weld A-3 (400 F (204 C) preheat). Metallurgical examination of crack surfaces revealed ductile rather than cleavage fractures. These results lead to the conclusion that the cracking under study was not the result of hydrogen and could not be prevented by increasing the preheat temperature to 550 F (288 C).

Influence of Weld Bead Contour

Hot cracking is known to be influenced by weld bead contour and the ratio of weld bead width to depth. Literature[1] indicates that a concave carbon steel weld bead, whose depth is greater than 1.25 to 1.5 times its width, is the most sensitive to center bead cracking. This sensitivity occurs because solidification begins at the fusion lines of a fillet weld and the center portion is the last to solidify. Shrinkage strains during solidification and cooling after solidification place the center of the weld bead in tension. If a liquid film exists between dendrites just prior to final solidification, the liquid cannot withstand shrinkage strains, and the dendrites are pulled apart forming a solidification crack. After solidification, during cooling of the weld bead, cracks may also form in segregated zones or in mixed phases within the weld microstructure because of the inability of these zones or phases to withstand shrinkage strains.

A series of weld tests was made to examine the influence of weld bead contour on center bead cracking. The concave contour of test weld A-3 containing a center bead crack is shown in Fig. 4. Weld A-3 and the cracked weld shown in Fig. 3 have width-to-depth ratios of 2.5. A concave weld bead with a width-to-depth ratio of 2.16 was produced by decreasing penetration using straight polarity welding current in test weld C-1. As noted in Table 1, test weld C-1 cracked. Weld D-4 in Fig. 5 had a flat external contour, a width-to-depth ratio of 1.33, and cracked severely.

Figure 6 shows weld C-4 which did not crack. Weld C-4 has a width-to-depth ratio of only 1.22 and an extremely convex contour. This contour is not desirable because it has severe notches at the weld toes. These notches are not only stress concentrations but are susceptible to entrapped slag during multiple-pass welding.

These tests showed that bead contour has an effect on weld cracking resistance in martensitic stainless steels. For a given wire and flux combination, which produced cracks in flat and concave beads, no cracks occurred in a convex bead. Similar results were found for shielded metal arc welding with E-410-16 electrodes. Weld H-4 which had a flat or slightly concave contour did not crack, yet welds P-1 through P-4, which were concave, did crack.

No precise relationship was determined between width-to-depth ratio and cracking susceptibility. Certainly, the rule of thumb which applies to carbon steels cannot be applied directly to Type 410 stainless steel weld metal. It was also concluded that the weld contour which would prevent cracking in Type 410 submerged arc welds was so convex that it did not represent an acceptable solution to the problem.

Weld Chemistry and Microstructure

Weld microstructure is determined by weld chemistry and cooling rate. Weld metal is comprised of base metal, filler metal and alloying elements from the flux. The concentration of alloying elements in the weld metal due to the filler metal is not what would be expected based on base metal/filler metal dilution alone. Certain alloying elements are not completely transferred across the welding arc and others are affected by reactions with the flux. Test welds were made to determine the effect of four fluxes and three filler metals on weld metal chemistry and microstructure.

Table 3—Weight Changes in Weld Metal Chemistry Resulting from Flux Reactions for Submerged Arc Welding Type 410 Stainless Steel with Type 410 Filler Metal "A," 200 A, 30 V, 10 ipm (254 mm/min.) Travel Speed, %

Flux #	C[a]	Mn	Si	Cr	Ni	Mo[a]
1	NC	Gain .30	Gain .40	Loss .93	Gain .05	NC
2	NC	Gain .34	Gain .30	Loss .30	Loss .04	Loss .13
3	NC	Gain .22	Gain .55	Gain .34	Gain .02	NC
4	NC	Gain .50	Gain .16	Gain .86	Gain .28	NC

[a] NC—no change; changes in these elements were too small to be statistically significant.

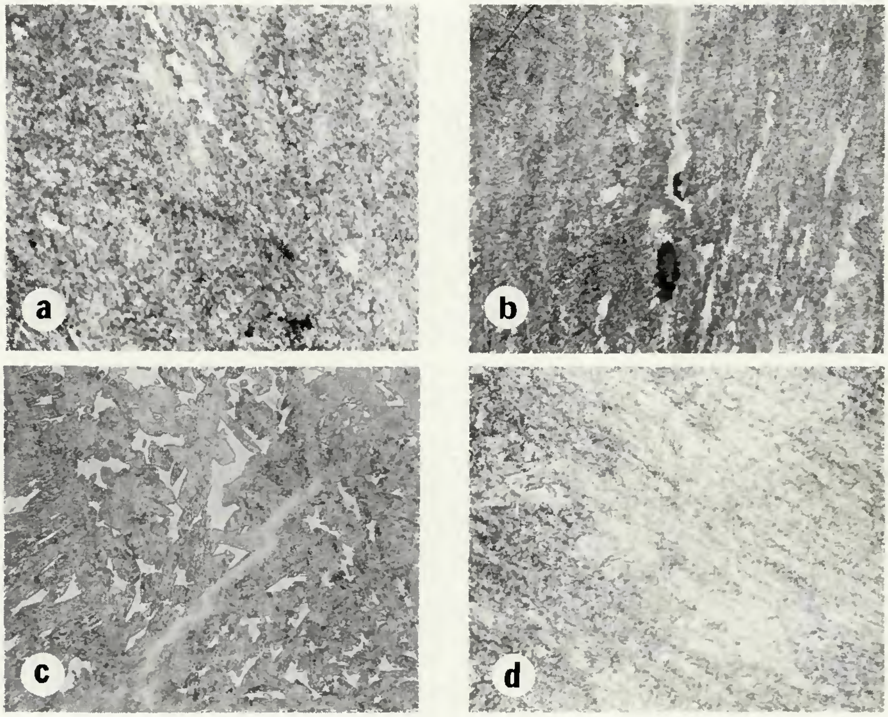

Fig. 7—Martensite microstructures with varying chromium equivalents: A (top left)—test weld A-1 with 2.3% ferrite; 9.41 chromium equivalent. B (top right)—test weld A-3 with 11.5% ferrite; 10.48 chromium equivalent. C (lower left)—test weld D-4 with 10.8% ferrite; 9.30 chromium equivalent. D (lower right)—test weld M-1; 4.16 chromium equivalent. Marbles etchant for A, B and C; oxalic etchant for D. ×100 (reduced 28% on reproduction)

Effects of Welding Flux

Test welds A-3, E-2, E-3 and E-4 were made with Type 410 stainless steel electrode "A," identical welding conditions (200 A, 30 V, 10 ipm (254 mm/min)) and four different fluxes. Two neutral fluxes (Fluxes #1 and #2) and two slightly alloyed fluxes (Fluxes #3 and #4) were used.

Figure 4 shows that the concave fillet produced by these welding conditions is composed of 48.6% base metal and 51.4% filler metal. Using the chemical compositions of the filler metal and base metal (cruciform bar), an expected weld chemistry was calculated based upon the above dilution rate.

The effects of each flux on chemistry were determined by comparing these theoretical chemistries to actual weld metal chemistries—Table 2. The comparisons revealed that chromium was lost during metal transfer or slag reaction when either Flux #1 or Flux #2 was used. Calculations showed a 14% chromium loss with Flux #1 which approximately agrees with Jackson and Shrubsall[2] who reported an 18.8% chromium loss when welding 12% chromium steels with Flux #1.

Oxides of iron, manganese, and silicon in the flux are easily reduced by chromium during welding. A portion of filler metal chromium is transferred to the molten slag, while manganese and silicon from the flux are transferred to the weld metal. Table 3 shows that all fluxes transfer silicon and manganese to the weld metal. Fluxes #3 and #4 are formulated for stainless steel welding and contain extra chromium to replace chromium losses in the arc. Flux #4 also transfers significant nickel to the weld metal.

Table 3 summarizes the influence on weld metal chemistry of the four fluxes studied. While each flux produced significant changes in weld metal chemistry, Table 1 shows that none of these changes prevented cracking.

Effects of Welding Electrode

The chemistries of two Type 410 stainless steel electrodes are shown in Table 2. Weld A-1 was made using Type 410-B electrode and Flux #1 at 200 A, 30 V, and 10 ipm (254 mm/min.). Weld A-3 was identical to A-1 except that Type 410-A electrode was used.

The differences in weld metal chemistries between these two welds are shown in Table 2. Both welds had a microstructure of martensite and ferrite as shown in Fig. 7A and 7B. The ferrite content of weld A-1 was estimated to be 2.3% and that of weld A-3 to be 11.5%. Both electrodes have a history of weld cracking and also cracked during cruciform testing. The Type 410-A electrode produced more numerous and larger cracks than did Type 410-B electrode, however.

A series of welds were made with a modified Type 410 electrode which nominally contains 4% nickel and 0.5–1.0% molybdenum. Several manufacturers designate this Type 410-Ni-Mo or Type 410-Ni. A variation which replaces some molybdenum with titanium is designated AM-363 alloy.

AM-363 electrode was available and was used to make test welds G-3, G-4, I-1 through I-4, M-1 through M-4, and N-1 through N-4. Flux #1, Flux #4 and Flux #3 were used, and welding parameters produced concave weld contours. The chemistries of typical welds are listed in Table 2 along with the chemistry of the electrode, itself. No cracks were found in any weld made with the AM-363 electrode.

The weld microstructure shown in Fig. 7D contains no free ferrite. Additional welds 0-1 through 0-4 were made with AM-363 electrode and Flux #1 using a cruciform made from Type 410 Cb stainless steel. No cracks were found in these welds either.

Hardness measurements showed that the AM-363 weld was slightly harder (higher in strength) than straight Type 410 welds. Type 410 welds stress relieved at 1100–1200 F (600–650 C) had hardnesses of 24–29 Rc while the welds made with AM-363 ranged from 24-32 Rc after the same stress relief treatment.

The effects of weld metal chemistry on weld microstructure can be seen by use of Thielemann's[3] chromium equivalent equation:

$$\textit{Chromium Equivalent} = -40(C) - 3(Ni) - 2(Mn) - 1(Cu) + CR + 2.1(W) + 2.8(Ta) + 4.2(Mo) + 4.5(Cb) + 5.2(Si) + 7.2(Ti) + 11(V) + 12(Al)$$

Austenite forming elements are negative quantities and ferrite forming elements are positive quantities in this equation. Therefore, the larger the positive result of this equation, the stronger the chances of forming ferrite in the microstructure of an alloy. Chromium equivalents computed from the chemistries are listed in Table 2.

The chromium equivalents are not absolute, because the nitrogen levels of welds were not measured. However, the chromium equivalents do give an index of comparison between chemistries, assuming nitrogen levels to be nearly equal. Chromium equivalents indicate that Type 410-B electrode produces less ferrite than Type 410-A electrode, all other conditions the same, chiefly due to the higher carbon content of Type 410-B electrode. Flux #1 produces a weld with a lower chromium equivalent than Flux #3 or Flux #4 because of chromium losses. Welds made with Flux #4 have lower chromium equivalents than those made with Flux #3 due to the increased nickel content. The AM-363 electrode produces a significantly lower chromium equivalent in the weld due to its 2.0–2.6% nickel content.

The shielded metal arc weld H-4 had a high chromium equivalent due to its high chromium content. Measurements of ferrite contents showed that Type 410-B electrode and Flux #1 produced 2.3% ferrite while welds made with Type 410-A electrode contained 10–13% ferrite. Type E-410-16 shielded metal arc electrodes also produced welds with 10–13% ferrite.

Summary of Weld Tests

Cruciform tests revealed that weld cracking could be eliminated using Type 410 stainless steel electrodes only if a very convex weld bead was produced. However, this bead contour is unacceptable for many applications.

A crack-free, concave weld bead with a chromium content comparable to Type 410 welds can be produced using AM-363 electrode and the same welding conditions previously used with Type 410 electrodes. Furthermore, E-410-16 shielded metal arc electrodes are also susceptible to cracking, particularly when weld beads are concave. Type E-410-Ni shielded metal arc welding electrodes were shown to be as crack-resistant as the AM-363 weld metal.

Procedure Qualification and Shop Trial

Two welding procedures shown in Fig. 4 were qualified on 0.5 in. (12.7 mm) thick Type 403 stainless steel plate. Single bevel joints with 0.125 in. (3 mm) root gaps and backing strips were welded using AM-363 electrode. These joints were welded, stress requirements of Section IX, ASME Boiler and Pressure Vessel Code.

Both welds successfully passed procedure qualification testing. Mechanical properties of the two weld joints are shown in Table 4. Procedure N produces a weld chromium content in excess of 12% while procedure M, using Flux #1, has a chromium content of slightly below 12%.

Following successful cruciform and procedure qualification testing, the welding procedure using AM-363 electrode and Flux #1 was used in production. The only change between the new procedure and that previously used was in the electrode; all other variables including flux were the same. Welds were concave, and no difficulties were experienced during welding. After stress relief, magnetic particle inspection revealed no cracks.

Explanation of Cracking Mechanism

A review of laboratory cruciform tests showed that three things were necessary to cause cracking in Type 410 fillet welds:

1. Sufficient restraint to concentrate shrinkage stresses in the weld throat.
2. A flat or concave weld bead contour.
3. A crack sensitive microstructure containing delta ferrite.

Further analysis of these tests indicated that the cracking occurred at a high temperature. This conclusion was drawn because the pattern of crack formations had been observed on solidified welding slag carefully removed from welds. Also, a particle of slag had been identified within a crack in one test specimen.

Solidification cracking is a common hot cracking mechanism which occurs near or slightly below the solidus temperature of the material. Solidification cracking occurs in austenitic stainless steel as well as carbon-manganese steel weld metals. The most widely accepted theory for solidification cracking which relates its cause to segregations and low melting point phases at grain boundaries between solidifying dendrites is widely reported in the literature.

Elements which contribute most to solidification cracking are those which form low melting point alloys. In steel, these detrimental elements are sulfur, phosphorous, lead, tin, zinc, aluminum, and in certain steels carbon and nickel.[1-6] It was concluded that the cracking under study was not liquation, solidification cracking which occurs near the solidification temperature range of 2500–2700 F (1370–1480 C) for the following reasons:

Table 4—Procedure Qualification Welding Conditions and Results of Testing to Section IX, ASME Boiler and Pressure Vessel Code

Welding Parameters	Procedure "M"	Procedure "N"
Base material	Type 403	Type 403
Base material Thickness	0.5 in. (12.7 mm)	0.5 in. (12.7 mm)
Welding process	SAW	SAW
Weld joint	60 deg-V	60 deg-V
Position	Flat (1G)	Flat (1G)
Electrode	AM-363	AM-363
Electrode diameter	0.062 in. (1.6 mm)	0.062 in. (1.6 mm)
Flux	Flux #1	Flux #4
Electrode stick-out	0.75 in. (19 mm)	0.75 in (19 mm)
Preheat temperature	400-500 F (204-260 C)	400-500 F (204-260 C)
Welding current	200 A	200 A
Welding voltage	30 V	30 V
Travel speed	14 ipm (355 mm/min.)	14 ipm (355 mm/min.)
Polarity	DCRP	DCRP
Stress relief	2 h 1100 F (593 C)	2 hr 1100 F (593 C)
ASME Section IX Testing		
Tensile bar #1[a]		
Tensile strength	80,100 psi (552 MPa)	79,500 psi (548 MPa)
Yield strength	46,800 psi (323 MPa)	47,500 psi (327 MPa)
Elongation	25%	22.5%
Tensile bar #2[a]		
Tensile strength	79,700 psi (549 MPa)	80,200 psi (553 MPa)
Yield strength	46,300 psi (319 MPa)	48,900 psi (337 MPa)
Elongation	23.5%	22.5%
Side bend #1	No Defects	No Defects
Side bend #2	No Defects	No Defects
Side bend #3	No Defects	No Defects
Side bend #4	No Defects	No Defects
Charpy V-notch tests:		
−25 F (−32 C)	No test	21 ft-lb (28.5 J)
25 F (−3.9 C)	11 ft-lb (15 J)	23 ft-lb (31 J)
75 F (24 C)	15 ft-lb (20 J)	28 ft-lb (38 J)

(a)All tensile bars failed in the base metal.

1. No lead or zinc and only traces of tin were found in cracked Type 410 stainless steel welds.

2. Sulfur and phosphorous levels were no lower in crack free welds made with AM-363 electrode than in cracked Type 410 welds (see Table 2).

3. Since nickel increases the solidification range of 12% chromium steel, nickel additions should promote solidification cracking, not prevent it. Nickel was found beneficial in the present study.

4. No correlation could be found with Huxley's crack sensitivity factor which has been shown to have good correlation to hot cracking in many types of steels.[6,7]

The approximate temperature of cracking under study was estimated in the following manner. It has been stated that reproductions of cracks had been observed on the underside of solidified slag and that a slag inclusion was identified by microprobe analysis within a crack in a Type 410 stainless steel weld. This indicated that cracking occurred while slag was still fluid enough to enter the crack. Jackson[10] reported that the viscosity of molten submerged arc slag greatly increased in the temperature range of 2100-2200 F (1150-1200 C). While this fact alone did not pinpoint the cracking temperature, it did suggest a minimum temperature range. Metallurgical examination of the quantity of oxide on crack surfaces indicated cracking occurred above 1600 F (870 C). Therefore, it was concluded that the cracking observed took place between approximately 1600 and 2500 F (870 and 1370 C).

An analysis of all data collected during cruciform welding showed a correlation between weld metal ferrite content and cracking susceptibility. Ferrite is known to be beneficial in the prevention of solidification cracks in austenitic stainless steel weld metal,[8] and Type 410 weld metal is austenite and ferrite as solidification occurs. However, the ferrite in Type 410 welds observed in this study was not uniformly distributed at austenite grain boundaries. Ferrite appeared to adversely influence cracking in Type 410 steel.

Type 410 stainless steel which contains ferrite of 5-15% is subject to hot tearing if it is hot forged in the temperature range of 2000-2300 F (1090-1260 C). The strong effects of ferrite in reducing transverse ductility and notch toughness of wrought and forged 12% chromium steels are well documented.[12-14]

Based upon a survey of literature, no detailed reports of cracking similar to that under study could be found. Therefore, the following cracking mechanism has been formulated to explain the cracking observed during the present study:

In the temperature range where cracking is suspected to occur—1600-2500 F (870-1370 C)—Type 410 weld metal has completely solidified and consists of delta ferrite and austenite. This solid, duplex structure is subjected to stresses resulting from the contraction of the weld bead and surrounding base metal.

Fabrications which produce high restraint and weld beads with concave contours concentrate shrinkage stresses on the weld throat. Thus at high temperature where austenite is stronger than ferrite, strains are concentrated in ferrite grains or austenite/ferrite grain boundaries, causing slip even at low stress levels. Under these conditions, fine cracks may develop within ferrite grains (or planes of weakness may develop at ferrite/austenite grain boundaries), even at strains below those required to produce deformation of the austenite.

As microcracks develop, shrinkage stresses are transferred to surrounding austenite areas. However, local stresses are multiplied by the stress concentrations caused by microcracks. As cooling continues and austenite transforms to martensite, cracks may propagate as shrinkage stresses continue to rise.

If this cracking mechanism is correct, cracking should be prevented by one of the following:

1. Changing the distribution of shrinkage stresses through changes in bead contour.

2. Reducing restraint.

3. Eliminating the mixed ferrite/martensite microstructure.

The results described earlier showed that these changes did indeed prevent cracking. The final solution, the elimination of delta ferrite from the weld microstructure, was accomplished with the chromium/nickel welding electrode.

Conclusions

1. Single pass Type 410 fillet welds on Type 403/410 steel which have flat or concave contours are susceptible to longitudinal center bead cracking.

2. A cruciform test specimen was successfully used to produce sufficient restraint so that this type of cracking could be studied in the laboratory.

3. Center bead cracking when using Type 410 stainless steel filler metal could be eliminated only when parameters were adjusted to produce a very convex weld contour. This contour was unacceptable, however, because of the high stress concentration and difficulty of preventing slag inclusions at weld toes.

4. Center bead cracking could not be eliminated using any of the Type 410 shielded metal arc electrodes, Type 410 submerged arc welding electrodes or any of the four fluxes evaluated during this laboratory investigation.

5. Center bead weld cracking was eliminated by using a 12% chromium-4% nickel-molybdenum welding electrode in place of the previously used Type 410 electrode. No other changes in welding flux or procedure were made. The resulting bead had a concave contour.

6. This new electrode was successfully used to weld production parts without cracking.

7. Type E-410-16 SMAW electrodes are also susceptible to cracking, and Type E-410 Ni electrodes are recommended for these applications.

8. Cracking in Type 410 welds is not believed to be the type of solidification cracking which occurs near the solidus temperature of a material due to segregation and liquation. Instead, the cracking studied during this program is believed to occur between approximately 1600 and 2500 F (870 and 1370 C).

To produce the cracking studied in this program, the weld bead must have a flat or concave contour, restraint must be high enough to concentrate shrinkage stresses on the weld throat, and the weld microstructure must be two-phase, ferrite and austenite (martensite at lower temperatures). Given these conditions, shrinkage strains produced by weld bead cooling cause fracture of ferrite grains or fracture at austenite-ferrite grain boundaries. These microcracks produce stress concentrations and propagate into larger cracks as the weld continues to cool and shrinkage stresses continue to increase.

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