Weldability of Low Alloy Steels for Line Pipe Fittings

Susceptibility of welds to underbead cracking in carbon-manganese steels can be used to evaluate acceptability of proposed specifications for steels for line pipe fittings

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ABSTRACT. With the increased interest in line pipe for use in arctic service, new steels and new specifications are being developed which include more stringent requirements for low temperature notch toughness. Coupled with these new requirements is a greater attention to weldability. As part of a program to develop steels that meet these new requirements, a statistically designed investigation was conducted to determine the effects of carbon, columbium, vanadium, aluminum, and nitrogen on the weldability of 1.2 Mn, 0.2 Si steels in the quenched and tempered condition.

Because line pipe fittings are field welded and weldability is part of the proposed specifications for these steels, the susceptibility of the steels to weld underbead cracking was investigated. For this study, longitudinal bead-on-plate underbead cracking tests were conducted on fifty-one 1.2 Mn, 0.2 Si steels. The underbead cracking test results showed the expected strong correlation between underbead cracking tendency and carbon content. The results did not rule out columbium, vanadium, aluminum, and nitrogen as factors affecting underbead cracking; however, they indicated that the effects of these elements, if any, are minor and not significant enough to limit their use at the levels being suggested for steels of this type. The data in this study can also be used to indicate chemical composition limits for meeting underbead cracking test requirements in weldability specifications.

Introduction

With the increased interest in material for applications such as line pipe to be used in arctic service, new steels and new specifications are being developed which include more stringent requirements for low temperature notch toughness. Coupled with these new requirements is a greater attention to weldability. As part of U.S. Steel's programs to develop steels that meet these new requirements, a study was conducted to develop improved heat treated plate steels. The specific application intended was line pipe fittings; however, the results apply to many other structural applications. As part of this study, a statistical program to investigate the effects of carbon, columbium, vanadium, aluminum, and nitrogen on the weldability of 1.2 Mn, 0.2 Si steels in the quenched and tempered condition was conducted and is reported here.

Materials and Experimental Work

All the steel plates used in this study were obtained from 300 lb (135 kg) air induction melted heats. All the plates were 1 in. (25.4 mm) thick, and the longitudinal-to-transverse cross rolling ratio was 2 to 1. The plates were shot blasted, heated to 1650 F (900 C), held for 1 h, and quenched in agitated water. The quenched plates were tempered at 1150 F (620 C) for 50 min at temperature and air cooled.

A total of 51 heats were included in the program. Thirty of the heats (steels No. 1 through 30) were a sta-

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tistically designed series. These heats had a base composition of 1.20 % Mn, 0.015 % P, 0.015 % S, 0.22 % Si, with low residuals; the variable elements were carbon (0.06 to 0.22 %), columbium (0 to 0.045 %), vanadium (0 to 0.13 %), aluminum (0 to 0.06 %), and nitrogen (0.005 to 0.027 %) (center point, 0.15 % C, 0.015 % Cb, 0.04 % V, 0.02 % Al, and 0.012 % N). Seven of the heats (steels No. 31 through 37) contained residual elements (Cu, Ni, Cr, or Mo). The other 14 heats (steels No. 38 through 51), which were outside the aim composition ranges, were included in the program because they furnished additional data. The chemical compositions of all 51 steels are shown in Table 1.

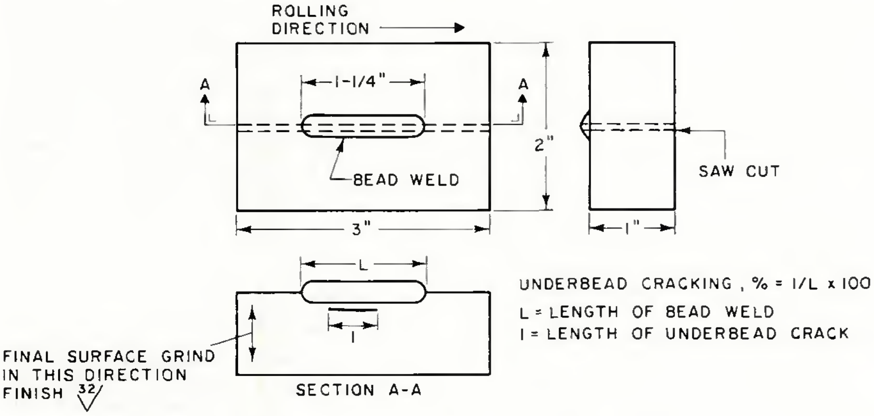
Underbead Cracking Tests

The longitudinal bead-on-plate underbead cracking test specimen is shown in Fig. 1. One set of specimens (five per set) was machined from each steel and welded by the shielded metal-arc (SMA) process at 70 F (21 C) with cellulose covered E6010 electrodes. Four additional sets were machined from 14 of the steels (11 from the statistical program and 3 of the related steels). Three of these four sets were SMA welded with E6010 electrodes — one set each at 120, 150, and 212 F (49, 66, and 100 C); the fourth set was SMA welded at 70 F with low hydrogen, iron powder, E7018 electrodes. Temperature control during welding was obtained by partially immersing the specimens in a controlled temperature water bath. The SMA welding conditions listed in Fig. 1 were used to deposit the weld beads on the specimens.

After deposition of the weld beads, the specimens were aged at room temperature for at least 24 h, postweld heat treated at 1100 F (593 C) for 1 h, and then saw cut into longitudinal sections and surface ground. The surface ground specimens were examined for underbead cracking by the wet magnetic particle method. The amount of underbead cracking in each specimen was expressed as a percentage obtained by dividing the imens was obtained by dividing the total length of underbead cracks by the total length of weld beads for all the specimens in a set.

Nature of Underbead Cracking

Underbead cracking originates in the heat-affected zone (HAZ) of the base metal after welding. The cracking can occur soon after the weld has cooled sufficiently to transform or may be delayed for a considerable time. The cracks are generated through the embrittling effects of hydrogen on a predominantly martensitic structure which is subjected to the stresses due to the austenite to martensite transformation and to restraint. Weldable structural and pressure vessel steels have a negligible susceptibility to underbead cracking provided suitable care is taken to limit hydrogen in the welding atmosphere to a tolerable amount. However, steels differ in the amount of hydrogen tolerated, depending on the chemical composition of the steel. Further, the cooling rate from welding, as influenced by preheat temperature, heat input, and plate thickness, can affect the amount of underbead cracking.



ELECTRODE	E7018	E6010
ELECTRODE DIAMETER , inch	1/8	1/8
CURRENT , amperes	100	100
ARC VOLTAGE , volts	22	25
SPEED OF TRAVEL , ipm	8.8	10.0
TYPE OF CURRENT	DC-RP*	DC-RP
HEAT INPUT , joules per inch	15,000	15,000

*DIRECT CURRENT – REVERSE POLARITY

Fig. 1 — Preparation of underbead cracking specimen and conditions used for welding 1 in. thick plates

For steels of the type used in this study, experience has shown that the amount of cracking generally increases as the preheat temperature is increased up to a certain temperature, above which it decreases rapidly with increasing temperature. This indicates that there is a specific cooling rate that will result in maximum underbead cracking for each type of steel when the steel is welded in an arc atmosphere sufficiently high in hydrogen content (Ref. 1). One explanation for this cooling rate effect is that at low preheat temperature the HAZ is almost completely martensitic and has a relatively uniform (and relatively low) carbon content. This structure is moderately crack susceptible. At higher preheat temperatures (with a corresponding slower cooling rate), the transformation of the HAZ is mixed, with ferrite precipitating first and the remaining austenite thereby becoming enriched in carbon. This enriched austenite then transforms at lower temperatures to a higher carbon martensite, which is more crack susceptible. At still higher welding preheat temperatures and slower cooling rates, martensite does not form and the HAZ is much less susceptible to cracking.

The susceptibility of a steel to underbead cracking is often related to its chemical composition by a carbon equivalent (C.E.) formula. Numerous formulas have been proposed since 1940 when a formula for predicting the HAZ maximum hardness in low alloy structural steels was proposed by Dearden and O'Neill (Ref. 2). Typical and frequently used formulas are as follows:

For C-Mn Steels (Ref. 1):

$$\text{C.E.} = \%\text{C} + \frac{\%\text{Mn}}{6}$$

For Low Alloy Steels (Ref. 2)
(Based on HAZ Hardness):

$$\text{C.E.} = \%\text{C} + \frac{\%\text{Mn}}{6} + \frac{\%\text{Cu} + \%\text{Ni}}{15} + \frac{\%\text{Cr} + \%\text{V} + \%\text{Mo}}{5}$$

For Low Alloy Steels (Ref. 3)
(Based on HAZ Cracking):

$$\text{C.E.} = \%\text{C} + \frac{\%\text{Mn}}{6} + \frac{\%\text{Ni}}{20} + \frac{\%\text{Cr}}{10} - \frac{\%\text{Mo}}{50} - \frac{\%\text{V}}{10} + \frac{\%\text{Cu}}{40}$$

Most formulas use a factor for manganese of Mn/6 or Mn/4; however, the

Table 1 — Chemical Composition of 1 In. Thick Plate Steels Used for Underbead Cracking Tests — wt % (Check Analysis)

Steel No.	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Aluminum Sol	Aluminum Total	N	Cb
1	0.21	1.14	0.016	0.017	0.22					<0.005	0.002	0.005	0.005	<0.01
2	0.11	1.20	0.015	0.014	0.24					<0.005	0.001	0.002	0.018	<0.01
3	0.11	1.17	0.015	0.014	0.23					<0.005	0.024	0.029	0.005	<0.01
4	0.20	1.18	0.016	0.016	0.24	<0.005	0.012	0.008	0.009	<0.005	0.034	0.041	0.018	<0.01
5	0.10	1.18	0.015	0.014	0.25					0.084	0.001	0.004	0.005	<0.01
6	0.21	1.14	0.016	0.016	0.20					0.087	0.002	0.007	0.020	<0.01
7	0.21	1.20	0.013	0.015	0.24					0.082	0.026	0.031	0.007	<0.01
8	0.11	1.16	0.016	0.012	0.23					0.083	0.022	0.027	0.018	<0.01
9	0.11	1.18	0.015	0.014	0.25					<0.005	0.001	0.002	0.005	0.029
10	0.22	1.21	0.016	0.015	0.20					<0.005	0.001	0.008	0.018	0.027
11	0.20	1.23	0.017	0.017	0.25	<0.005	0.002	0.008	0.010	<0.005	0.032	0.040	0.004	0.028
12	0.12	1.23	0.016	0.013	0.24					<0.005	0.024	0.031	0.019	0.032
13	0.22	1.12	0.015	0.015	0.22					0.074	0.002	0.005	0.005	0.029
14	0.11	1.17	0.014	0.015	0.21					0.084	0.001	0.005	0.018	0.030
15	0.11	1.17	0.016	0.013	0.21					0.082	0.028	0.034	0.007	0.031
16	0.20	1.20	0.017	0.017	0.24	<0.005	0.002	0.008	0.009	0.079	0.031	0.041	0.020	0.030
17	0.17	1.19	0.016	0.014	0.25					0.040	0.015	0.020	0.013	<0.01
18	0.16	1.20	0.017	0.015	0.23	<0.005	0.004	0.008	0.009	0.039	0.015	0.021	0.012	0.045
19	0.16	1.19	0.014	0.014	0.23					<0.005	0.015	0.019	0.013	0.016
20	0.17	1.18	0.018	0.014	0.23					0.13	0.014	0.022	0.013	0.015
21	0.17	1.19	0.017	0.015	0.24					0.040	0.002	0.006	0.014	0.017
22	0.20	1.25	0.013	0.014	0.25					0.039	0.058	0.066	0.014	0.014
23	0.15	1.20	0.016	0.015	0.24	<0.005	0.002	0.008	0.010	0.039	0.017	0.024	0.004	0.014
24	0.14	1.17	0.015	0.013	0.20					0.043	0.011	0.018	0.027	0.014
25	0.06	1.20	0.016	0.015	0.25					0.037	0.010	0.014	0.012	0.016
26	0.27	1.15	0.016	0.015	0.21					0.039	0.014	0.015	0.013	0.016
27	0.16	1.21	0.016	0.014	0.24					0.046	0.015	0.021	0.014	0.015
28	0.16	1.16	0.017	0.016	0.21					0.039	0.012	0.019	0.014	0.015
29	0.16	1.17	0.016	0.015	0.21					0.040	0.009	0.015	0.015	0.016
30	0.16	1.17	0.015	0.016	0.21	<0.005	0.015	0.008	0.009	0.038	0.018	0.023	0.014	0.014
31	0.16	1.18	0.016	0.016	0.21	0.16	0.16	0.15	0.065	0.039	0.010	0.012	0.014	0.015
32	0.16	1.22	0.015	0.015	0.21	0.23				0.037	0.018	0.023	0.005	<0.01
33	0.16	1.19	0.018	0.015	0.22	0.24				0.043	0.015	0.022	0.012	<0.01
34	0.16	1.19	0.015	0.014	0.22	0.23		0.26		0.038	0.014	0.020	0.007	<0.01
35	0.16	1.22	0.015	0.013	0.20	0.24		0.26		0.045	0.014	0.019	0.015	<0.01
36	0.16	1.21	0.017	0.016	0.23			0.26		0.038	0.017	0.023	0.006	<0.01
37	0.16	1.22	0.017	0.015	0.23	0.24		0.26		0.039	0.018	0.023	0.020	<0.01
38	0.16	1.20	0.015	0.016	0.26					0.043	0.013	0.019	0.021	0.018
39	0.20	1.26	0.011	0.015	0.40					0.077	0.001	0.005	0.018	<0.01
40	0.15	1.07	0.014	0.013	0.19					0.038	0.006	0.009	0.026	0.011
41	0.21	1.20	0.013	0.014	0.25					0.038	0.150	0.153	0.016	0.016
42	0.15	1.20	0.014	0.015	0.23					0.016	0.014	0.019	0.014	0.040
43	0.15	1.23	0.015	0.015	0.25					0.038	0.015	0.021	0.020	0.015
44	0.15	1.20	0.017	0.017	0.25					0.041	0.036	0.039	0.013	0.016
45	0.15	1.03	0.014	0.015	0.17					0.038	0.001	0.003	0.013	0.014
46	0.16	1.12	0.014	0.015	0.19					0.040	0.007	0.010	0.015	<0.01
47	0.20	1.15	0.017	0.016	0.23					0.083	0.005	0.011	0.016	<0.01
48	0.12	1.38	0.014	0.015	0.25					<0.005	0.005	0.011	0.021	<0.01
49	0.12	1.19	0.016	0.015	0.25					<0.005	0.004	0.012	0.006	0.031
50	0.06	1.20	0.017	0.015	0.23					0.039	0.018	0.025	0.013	0.014
51	0.15	1.43	0.016	0.014	0.21	0.16	0.15	0.16	0.062	0.040	0.021	0.028	0.019	0.014

Table 2 — Results of Longitudinal Bead-on-Plate Underbead Cracking Tests

Steel No.	Preheat temp.,		Electrode	Underbead cracking, % Individual values					Avg
	F	C							
1	70	21	E6010	11	33	22	50	43	32
2	70	21	E6010	0	0	6	0	0	1
3	70	21	E6010	0	0	0	0	0	0
4	70	21	E6010	57	50	31	48	54	48
5	70	21	E6010	0	0	0	0	0	0
6	70	21	E6010	73	75	71	73	65	72
7	70	21	E6010	30	67	62	29	23	42
8	70	21	E6010	0	0	0	0	0	0
9	70	21	E6010	0	0	0	0	0	0
10	70	21	E6010	57	71	74	62	50	63
11	70	21	E6010	86	69	77	67	52	70
12	70	21	E6010	0	0	0	0	0	0
13	70	21	E6010	59	67	62	73	56	64
14	70	21	E6010	0	0	0	0	0	0
15	70	21	E6010	0	0	0	0	0	0
16	70	21	E6010	70	69	64	86	82	74
17	70	21	E6010	7	7	7	10	13	9
	120	49		7	14	7	7	14	10
	150	66		13	3	3	9	3	6
	212	100		7	7	0	0	7	4
	70	21	E7018	0	0	0	0	—	0
18	70	21	E6010	33	33	7	43	40	33
	120	49		47	30	57	57	67	51
	150	66		32	34	36	47	48	40
	212	100		23	43	16	39	43	33
	70	21	E7018	0	0	0	0	—	0
19	70	21	E6010	1	11	18	16	7	12
	120	49		11	13	27	25	18	21
	150	66		24	23	31	33	23	27
	212	100		17	21	20	14	17	18
	70	21	E7018	0	0	0	0	—	0
20	70	21	E6010	44	15	30	38	12	28
	120	49		31	27	36	21	31	29
	150	66		7	19	27	30	13	19
	212	100		7	17	0	3	7	7
	70	21	E7018	0	0	0	0	—	0
21	70	21	E6010	44	14	10	11	24	21
	120	49		17	27	20	31	35	26
	150	66		7	38	25	20	17	21
	212	100		17	36	3	10	3	14
	70	21	E7018	0	0	0	0		0
22	70	21	E6010	72	50	79	60	61	64
	120	49		37	16	36	25	11	25
	150	66		30	33	7	3	0	15
	212	100		24	13	3	11	0	10
	70	21	E7018	0	0	0	0	—	0
23	70	21	E6010	25	11	57	25	23	28
	120	49		37	40	41	33	14	33
	150	66		42	23	27	31	35	32
	212	100		57	39	41	38	36	42
	70	21	E7018	0	0	0	0	—	0
24	70	21	E6010	6	6	14	14	5	9
	120	49		7	13	7	10	3	10
	150	66		6	3	3	0	7	4
	212	100		0	0	0	0	—	0
	70	21	E7018	0	0	0	0	—	0

choice of either of these two manganese factors is of little significance in the present study because the steels (except steels No. 45, 46, and 51) all had a nominal manganese content of 1.2 %. Silicon, at least up to 0.25 %, is not considered to affect cracking in most formulas. Even in the formulas which include a factor for silicon, only the absolute value of the C.E. would be changed because all the steels had a nominal silicon content of 0.22 %. Past studies have shown that when the percent underbead cracking is plotted as a function of C.E., there is negligible cracking up to a certain minimum critical C.E., after which the percentage of cracking increases sharply as the C.E. increases.

Results and Discussion

Statistical Program

The individual and average results of the underbead cracking tests made on each steel plate are shown in Table 2. The steels in the statistical program (steels No. 1 through 30) were used for a computer programmed regression analysis in which the average percent underbead cracking at 70 F (21 C) was used as the dependent variable, with carbon, columbium, vanadium, total aluminum, and nitrogen contents as the independent variables. As expected, the analysis showed a strong correlation between cracking and carbon content. The study also showed that columbium, total aluminum, and vanadium increased the percent cracking; however, the results were not statistically significant. The effect of nitrogen was negligible, and there were no significant interactions.

The precision of the statistical analysis was reduced by the nonlinearity of the relationships and the excessive scatter inherent in the underbead cracking test. (The use of five specimens in a set is considered to measure average underbead cracking within 20 %, (Ref. 4). This statistical analysis did not rule out columbium,

Table 2 — Continued

Steel No.	Preheat temp., F	C	Electrode	Underbead cracking, % Individual values					Avg
25	70	21	E6010	0	0	0	0	0	0
	120	49		0	0	0	0	0	0
	150	66		0	0	0	0	0	0
	212	100		0	0	0	0	0	0
	70	21	E7018	0	0	0	0	—	0
26	70	21	E6010	83	83	100	97	74	88
	120	49		87	87	79	60	87	80
	150	66		77	67	73	63	71	70
	212	100		63	83	83	87	74	78
	70	21	E7018	0	6	0	10	—	4
27	70	21	E6010	26	26	20	19	40	26
	120	49		27	23	43	20	18	18
	150	66		40	17	23	10	21	22
	212	100		14	20	7	10	17	14
	70	21	E7018	0	0	0	0	—	0
28	70	21	E6010	19	9	7	7	7	10
29	70	21	E6010	19	0	19	21	13	15
30	70	21	E6010	15	26	10	7	24	16
31	70	21	E6010	32	53	53	69	74	56
32	70	21	E6010	14	7	7	10	7	9
33	70	21	E6010	7	0	7	11	10	7
34	70	21	E6010	25	17	14	32	14	21
	120	49		32	31	26	28	35	30
	150	66		24	21	41	28	28	28
	212	100		43	32	21	24	37	32
	70	21	E7018	0	0	0	0	—	0
35	70	21	E6010	0	3	4	7	11	5
	120	49		33	17	11	21	20	20
	150	66		45	38	26	23	16	30
	212	100		13	11	7	13	10	11
	70	21	E7018	0	0	0	0	—	0
36	70	21	E6010	18	7	11	17	17	14
37	70	21	E6010	9	7	7	14	7	9
	120	49		14	14	11	23	14	15
	150	66		19	37	20	17	21	23
	212	100		7	7	7	3	10	7
	70	21	E7018	0	0	0	0	—	0
38	70	21	E6010	14	13	7	14	14	12
39	70	21	E6010	50	61	76	60	77	65
40	70	21	E6010	6	6	3	6	0	4
41	70	21	E6010	53	67	53	59	32	53
42	70	21	E6010	23	21	30	48	40	33
43	70	21	E6010	14	36	44	33	41	34
44	70	21	E6010	39	29	10	7	10	19
45	70	21	E6010	0	0	0	7	7	3
46	70	21	E6010	0	0	0	0	0	0
47	70	21	E6010	50	41	46	54	36	45
48	70	21	E6010	0	0	7	6	7	4
49	70	21	E6010	0	0	0	0	0	0
50	70	21	E6010	0	0	0	0	0	0
51	70	21	E6010	60	44	56	64	61	57

vanadium, aluminum, and nitrogen in the amounts studied (Cb up to 0.045 %, V up to 0.13 %, Al up to 0.06 %, and N up to 0.027 %) as factors affecting underbead cracking; however, it indicated that the effects of these elements, if any, are minor and not enough to limit their use at the levels considered normal for weldable steels.

Evaluation of Carbon-Equivalent Formulas and Specifications

Some specifications for line pipe and related products include C.E. and/or underbead cracking test requirements, along with chemical composition limits and mechanical property requirements. The data generated in this program can be used to evaluate the C.E. formula requirements as well as to indicate the ability of a particular C.E. to meet underbead cracking test requirements.

Plots of the underbead cracking data obtained at 70 F in this investigation are shown as a function of C.E. for the previously mentioned formulas in Fig. 2, 3, and 4, respectively. Note in Fig. 2 that the underbead cracking was negligible for steels with C.E. <0.30 and appreciable for steels with C.E. >0.37. All steels without residuals (steels No. 1 through 30 and 38 through 50) fell in a band, with carbon being the principal factor affecting both C.E. and percent underbead cracking. No significance could be attached to the effects of columbium, vanadium, aluminum, and nitrogen. Most of the steels with residuals (steels No. 31 through 37 and 51) also fell in this band.

For the Dearden and O'Neill (Ref. 2) formula, Fig. 3, the scatter for the steels without residuals is about the same as shown in Fig. 2; however, most of the steels with residuals exhibit less cracking for their C.E. than was experienced with the steels without residuals. This strongly indicates that the effect of residual ele-

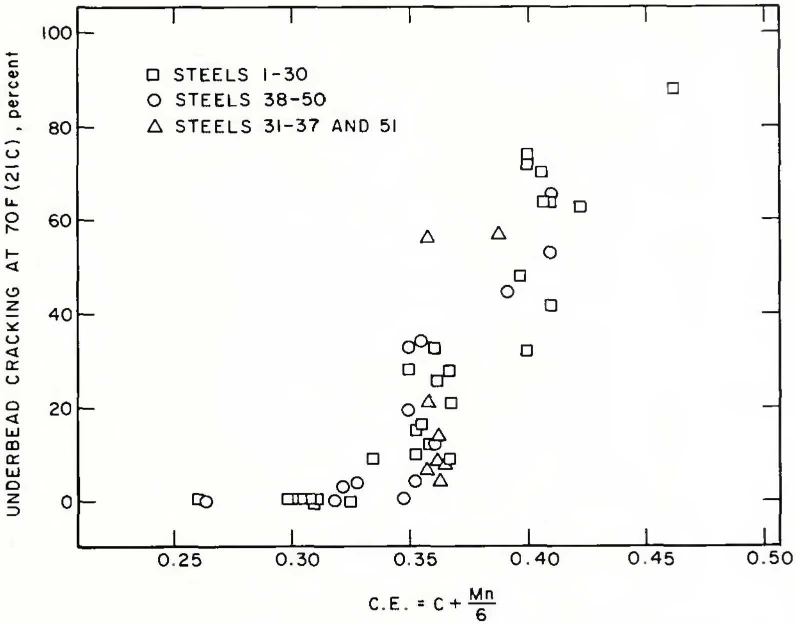
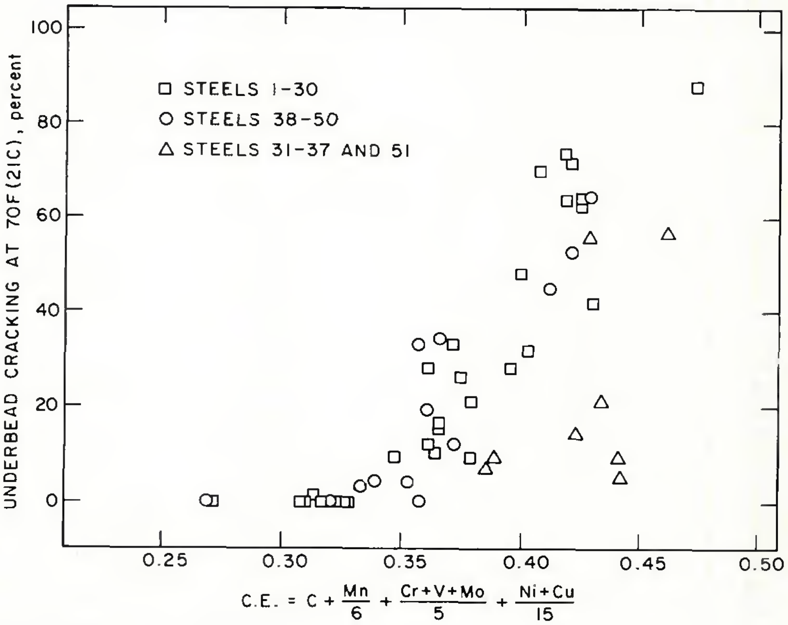


Fig. 2 — Underbead cracking vs carbon equivalent

Fig. 3 — Underbead cracking vs carbon equivalent



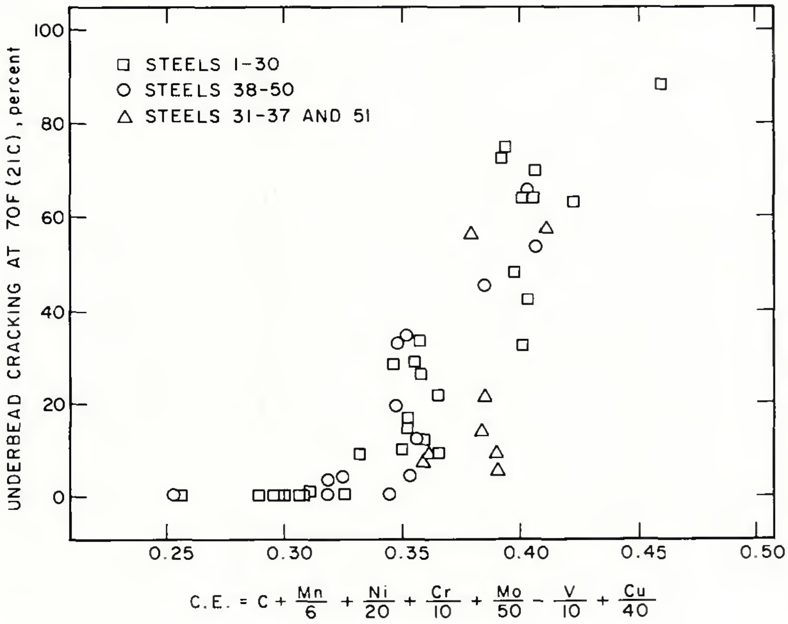


Fig. 4 — Underbead cracking vs carbon equivalent

ments, particularly chromium and copper, on underbead cracking is less than the Dearden and O'Neill formula would indicate. This effect is recognized by others (Ref. 5). However, this formula and close modifications of it have been used in proposed specifications as a measure of underbead cracking tendency, even though it was developed to predict maximum HAZ hardness.

When the Winterton formula (Ref. 3), which was based on underbead-cracking tendency, is used, the disparity between the steels with and without residuals is reduced, Fig. 4; however, the steels with residuals are still on the low side of the scatter band, which indicates that the residuals cause less cracking than the formula would indicate. This may be explained by the data in Fig. 5, which shows the difference in preheat temperature for maximum underbead cracking between steels with and without residuals. For this graph, the steels with a nominal carbon content of 0.15 % were used. This difference in preheat temperature effect can be explained on the basis that the increased hardenability of the steels with residuals shifted the critical cooling rate for maximum underbead cracking to a higher temperature without appreciably changing the magnitude of the maximum cracking.

For 14 of the steels, underbead cracking tests were conducted at 70 F preheat with low hydrogen, iron powder, E7018 electrodes. As expected, all these tests showed negligible cracking, Table 2.

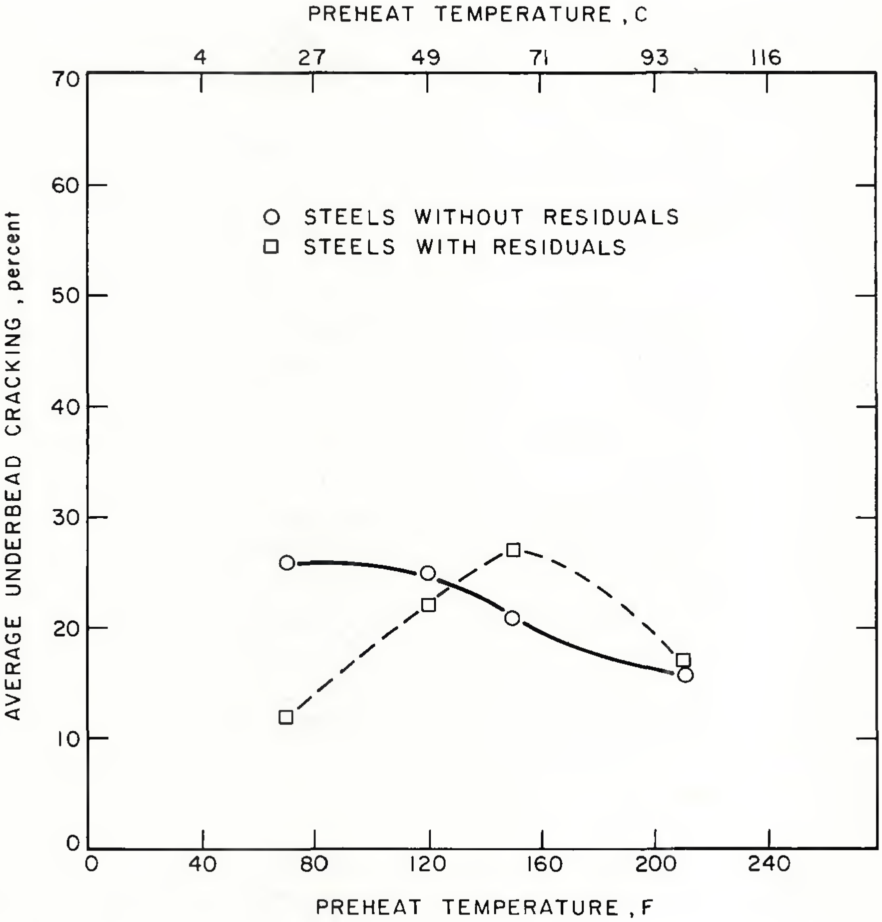


Fig. 5 — Effect of preheat temperature on underbead cracking

Summary

Longitudinal bead-on-plate underbead cracking tests were conducted on 51 laboratory produced plates of carbon-manganese steels with compositions of the type being considered for line pipe fittings for arctic service and similar applications. The primary purpose of the program was to determine the effects of columbium, vanadium, aluminum, and nitrogen on weldability.

The results of this study showed that the effects of these elements are minor and not enough to limit their use at least in the amounts generally considered normal for steels of the type studied. These data can also be used in the evaluation of carbon equivalent formulas and underbead cracking test requirements. In this connection these data indicate that the effect of residual elements on underbead cracking is less than some carbon equivalent formulas would indicate.

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"Improved Discontinuity Detection Using Computer-Aided Ultrasonic Pulse-Echo Techniques"

by J. R. Frederick and J. A. Seydel

The purpose of this project, sponsored by the Pressure Vessel Research Committee of the Welding Research Council, was to investigate means for obtaining improved characterization of the size, shape and location of subsurface discontinuities in metals. This objective was met by applying computerized data-processing techniques to the signal obtained in conventional ultrasonic pulse-echo systems. The principal benefits were improved signal-to-noise ratio and resolution.

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WRC Bulletin
No. 194
May 1974

"Fatigue Behavior of Pressure-Vessel Steels"

by J. M. Barsom

The regulations governing the design of pressure vessels are based on experience gained over many operational years and have evolved, primarily, to prevent failure under static load conditions. This design philosophy has been successful in ensuring adequate service behavior because pressure vessels are not usually subjected to large numbers of load fluctuations during their expected service life. However, the need to effectively utilize materials and to provide the utmost in safety and reliability has made it imperative to determine the fatigue behavior of these structures.

The fatigue life of structural components is determined by the initiation of cracks and their propagation to critical dimensions. This report presents fatigue-crack-initiation and fatigue-crack-propagation data for pressure-vessel steels operating in a benign environment and at temperatures below the creep region.

Data obtained by testing pressure vessels and pressure-vessel components, and the results of surveys of pressure-vessel failures are discussed. It is concluded that the probability of fatigue failure of properly designed and fabricated pressure vessels is very low and that the most effective approach to keep this probability low is to minimize the magnitude of the stress (strain) concentration factors. This can be accomplished through proper design of details and through proper fabrication.

This paper was prepared for the Pressure Vessel Research Committee of the Welding Research Council. The price of WRC Bulletin 194 is $4.50. Orders should be sent to the Welding Research Council, 345 East 47th Street, New York, N.Y. 10017.