

Effect of Aluminum on HAZ Cold Cracking in C-Mn Steels

New studies based on low hydrogen welding disagree with earlier reports concerning the effect of deoxidizing aluminum contents on cracking susceptibility

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ABSTRACT. Marked differences in the extent of heat-affected zone cold cracking in C-Mn structural steels containing different levels of aluminum have been reported by some investigators. A review of this work indicated certain anomalies. In an attempt to clarify this subject, controlled thermal severity (CTS) and bead-on-plate tests were made on C-Mn steels having carbon-equivalent values (% C + % Mn/6) of 0.44 to 0.47% and containing 0.008 to 0.011% N and <0.002 to 0.14% acid-soluble aluminum.

CTS specimens machined from rolled 1-in. plate, with a gap between top and bottom plates to increase test severity, showed almost no cracking at all levels of aluminum in laboratory produced steels, when welded at an energy input close to 33,000 joules/in. with E7018 low hydrogen electrodes containing 0.5% moisture. No cracking occurred in a commercial grade steel in similar CTS tests but in which greater restraint was imposed upon the weld by increasing the rigidity of the assembly. This steel contained aluminum in the range reported by other investigators to be associated with near peak cracking susceptibility.

The variations in cracking tendencies reported by other investigators were shown primarily by bead-on-plate tests in which welding was done using E6010 type electrodes that produced relatively large amounts of hydrogen in the arc atmosphere compared with the low hydrogen processes. Bead-on-plate tests, conducted by the author using E6010 electrodes, did not confirm the conclusions of other investigators that

there is a pronounced increase in cracking as acid-soluble aluminum increases from 0.002% or less to about 0.005 to 0.01%, or that cracking is reduced markedly at levels above about 0.02%. It was concluded that acid-soluble aluminum in the range of <0.002 to 0.14% had no significant influence upon cracking in the steels studied.

The virtual absence of cracking in the CTS tests made with low hydrogen electrodes indicated that little or no difficulty should be encountered due to cracking when steels of these compositions are welded with such electrodes in construction, provided that procedures are followed that are suitable for the carbon and manganese contents, the plate thickness, and the restraint factors involved.

Experience with the bead-on-plate test showed that test conditions must be controlled carefully and reported fully in order to facilitate comparison of test results.

Introduction

Conflicting results have been obtained by several investigators concerning the effect of aluminum upon the tendency for heat-affected zone (HAZ) cracking in welding of C-Mn steels. Due to the importance of aluminum as a steel additive, it was decided to undertake a program aimed at providing clarification of the effect of this element. This report summarizes relevant data from the literature and records heat-affected zone cold cracking studies completed to date by the author in an attempt to resolve this question.

Literature Review

Sims and Banta (Ref. 1) appear to have been the first to report the effect of aluminum upon weld heat-affected zone cracking in C-Mn struc-

tural steels. The effect was noted during an investigation on the influence of deoxidation practices upon Charpy V-notch properties. Cold cracking welding tests were performed as a subsidiary part of the study. In order to investigate further the relationship of aluminum and heat-affected zone cracking, tests were made on a series of six heats each having different levels of aluminum but with other elements being reasonably constant. The compositions of these steels, as well as of two "standard" laboratory heats used in the earlier studies, are shown in Table 1. The six laboratory heats were cast into 8 in. square ingots and rolled directly to 1 in. plate. No further details of production were given. The two "standard" heats were cast into 6 $\frac{3}{8}$ in. square ingots and forged at 1204 to 1260 C (2200 to 2300 F) into 2 \times 5 in. slabs. The slabs were reheated to 1204 C (2200 F) and hot rolled to 1 in. plate in six passes with the finishing temperature being about 954 C (1750 F). The plates were then placed on edge and allowed to air cool as in normalizing. All welding tests were made on the plate in the hot-rolled condition.

Cracking studies were made using the under-bead-cracking tests (Ref. 2), referred to subsequently as the bead-on-plate test. In this test, a 2 \times 3 \times 1 in. thick specimen was immersed to a level $\frac{1}{4}$ in. from its upper surface in a liquid at the desired test temperature. A modification from the test as described (Ref. 2) was that a flat groove 1/16 in. deep \times $\frac{1}{2}$ in. wide was machined in the 2 \times 3 in. top surface in order to eliminate any decarburized material in way of the weld deposit. Prior to welding, the specimens were stored at -18 C (0 F) and, during welding and for 10 seconds* afterwards, they were partially

*A modification of the one minute time interval described (Ref. 2).

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immersed in the liquid bath which was at -18°C (0°F). A $1\frac{1}{4}$ in. long weld bead was deposited with a $\frac{1}{8}$ in. E6010 electrode at 100 A, 24 to 26 V, and a travel speed of 10 in./min. Following welding, the specimens were held for 24 h at 16°C (60°F), tempered at 593°C (1100°F) for 1 h, sectioned longitudinally along the central axis of the weld, polished, and inspected by the magnetic particle method to reveal cracking. The percentage of cracked length of the weld heat-affected zone was calculated for each specimen. For each steel composition the corresponding cracking percentage was obtained by averaging the percentage cracking of ten specimens.

The results of this study are shown in Fig. 1. This indicates very little cracking (about 5%) in the absence of aluminum and a very rapid increase in cracking as the aluminum is increased to 0.003% and then to $<0.005\%$. Beyond about 0.01 to 0.02% Al, the cracking diminishes, although it is still about 60% at 0.06% Al and 18% at 0.18% Al.

Sims and Banta considered that the results just cited were still in need of verification. Consequently, three 450 lb induction furnace heats were made and each poured into two ingots. No aluminum was added to the heat prior to the first ingot, but then the remainder of the heat was deoxidized with an addition of 0.5 lb of aluminum/ton of steel and the second ingot was poured. The 6 $\frac{1}{2}$ in. square ingots were then processed into 1 in. plates as described earlier for their "standard" heats. The compositions of these steels and the bead-on-plate cracking results are reproduced in Table 2 and Fig. 2 respectively. It was concluded by the authors that these results supported their previous data and, thus, that small or medium amounts of aluminum for deoxidation would, in fact, cause a marked increase in cracking, while cracking could be reduced greatly by using either no aluminum or large additions such as 4 lb per ton.

In a study of the weldability of notch-ductile, C-Mn structural steels, Reeve (Ref. 3) compared the cracking tendency of the steels shown in Table 3 for which aluminum determinations had been made. Details of steel fabrication were not given. Controlled thermal severity (CTS) tests, as shown in Fig. 3, were made on all but plate No. 11, using cellulosic electrodes and also rutile electrodes in some cases. The only heat-affected zone cracking was in plates 4 and 7 which showed a maximum of about 6% and 10% cracking, respectively, in a few sections.

Bead-on-plate tests were also made by Reeve on all of the steels

Table 1 — Chemical Analysis (wt%) of Steels Used by Sims and Banta (Ref. 1)

Heat no.	C	Mn	P	S	Si	Ti	Al ^(a)	Al, lb/ton	Carbon equiv. ^(c)
X-23	0.20	1.25	0.021	0.022	0.27	0.007	Nil	0	0.41
X-24	0.23	1.36	0.019	0.021	0.29	0.006	<0.005	0.25	0.46
X-25	0.22	1.24	0.020	0.020	0.27	0.013	<0.005	0.5	0.43
X-26	0.22	1.31	0.021	0.021	0.27	0.016	0.029	1	0.44
X-27	0.20	1.29	0.018	0.020	0.31	0.015	0.064	2	0.42
X-28	0.22	1.26	0.019	0.020	0.27	0.015	0.180	5	0.43
X-45 ^(b)	0.21	1.35	0.021	0.030	0.27	0.015	0.003	0.4	0.44
X-46 ^(b)	0.22	1.35	0.023	0.032	0.28	0.015	0.003	0.4	0.45

(a) Acid-soluble aluminum content

(b) Heats X-45 and X-46 the standard composition steels

(c) $\% \text{C} + \frac{\% \text{Mn}}{6}$

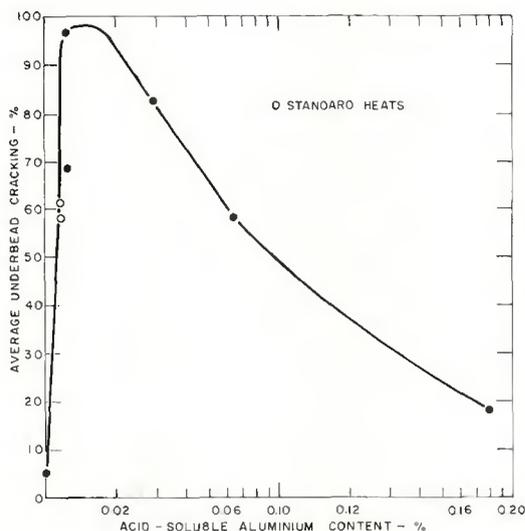


Fig. 1 — The effect of aluminum content upon underbead cracking (Sims and Banta, Ref. 1)

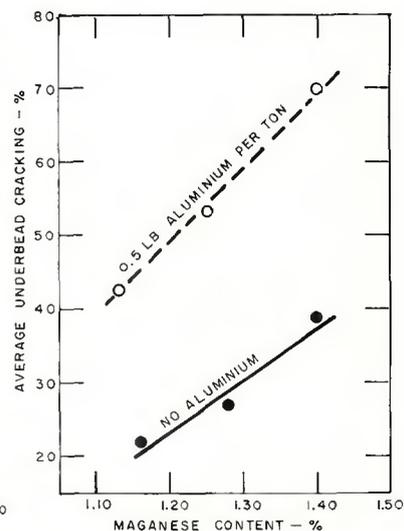


Fig. 2 — The effect of aluminum and manganese contents upon underbead cracking (Sims and Banta, Ref. 1)

Table 2 — Chemical Analysis (wt %) of Split Heats Used by Sims and Banta (Ref. 1)

Heat no.	C	Mn	P	S	Si	Ti	Al	Al, lb/ton	Carbon equiv. ^(a)
X-29	0.21	1.16	0.023	0.024	0.20	0.008	Nil	0	0.40
X-29A	0.21	1.13	0.019	0.025	0.17	0.008	0.005	0.5	0.40
X-31	0.22	1.28	0.023	0.027	0.26	0.008	Nil	0	0.43
X-31A	0.21	1.25	0.023	0.026	0.24	0.006	0.005	0.5	0.42
X-33	0.21	1.40	0.022	0.025	0.26	0.009	Nil	0	0.44
X-33A	0.21	1.40	0.022	0.024	0.24	0.007	0.005	0.5	0.44

(a) $\% \text{C} + \frac{\% \text{Mn}}{6}$

Table 3 — Chemical Analysis (wt %) of Steels Used by Reeve (Ref. 3)

Plate no.	C	Mn	P	S	Si	Al ^(a)	Carbon equiv. ^(b)
4	.18	1.34	0.034	0.047	0.20	Nil	0.40
7	0.20	1.24	0.020	0.037	0.06	Nil	0.41
2	0.16	1.17	0.023	0.029	0.05	0.002	0.36
1	0.16	1.44	0.028	0.028	0.14	0.004	0.40
8	0.16	0.87	0.029	0.040	0.04	0.004	0.30
9	0.18	0.90	0.027	0.042	0.05	0.004	0.33
11	0.15	1.09	0.036	0.044	0.21	0.013	0.33

(a) Acid-soluble aluminum content

(b) $\% \text{C} + \frac{\% \text{Mn}}{6}$

listed in Table 3. The procedure was to be as outlined by Stout and Doty (Ref. 2). Specimens were to be immersed in water at 10 to 20 C (50 to 68 F) at the start of the test. The only steels that showed any cracking in these tests were plates 7 and 11 for which cracking was reported as 7% and 1% respectively.

The weldability testing was done by a number of organizations and the data was studied and reported by Reeve. He concluded that there did not appear to be any association between the aluminum content and the extent of cracking.

Hasebe (Refs. 4 and 5) reported bead-on-plate cracking tests on C-Mn steels having the composition shown in Tables 4 and 5. No details of the fabrication of the steels were given. The steels were tested in both "as cast", and forged and normalized conditions. As shown in Fig. 4, the forged steels, with 0.006 to 0.008% N, showed a small increase in cracking in bead-on-plate tests as the acid-soluble aluminum increased from 0.002 to about 0.01% and then a generally gradual decrease in cracking at higher levels of aluminum. In forged steels with 0.025 to 0.035% N, cracking remained unchanged at alu-

minum contents up to 0.04% and then dropped rapidly at higher levels, being almost zero at aluminum contents of 0.12 and 0.16%. Cast steels of the same composition as the forged steels with 0.006 to 0.008% N showed an increase in cracking as aluminum levels increased from 0.002 to 0.01%, followed by a modest decrease in cracking with aluminum between 0.01% and 0.04 to 0.05% and no further significant change at aluminum contents of 0.12 and 0.17%.

Controlled thermal severity cracking studies, as well as the bead-on-plate studies discussed above, were reported by Hasebe on the same forged steels as shown in Tables 4 and 5. Welds were said to have been deposited using a 3.2 mm JIS-D4311 electrode (presumably equivalent to an AWS or CSA E6010 electrode), at 100-110 A, 20-24 V and at 8 in./min for the CTS tests and 10 in./min for the bead-on-plate tests. No other details of the bead-on-plate test procedure were found in references 4 or 5. Reference 5 shows that the CTS specimen employed was as illustrated in Fig. 3; i.e., the same type of specimen as used in studies reported by Reeve (Ref. 3). All of the steels were tested using CTS assemblies made from 1/4, 1/2 and 1 in. plate with the top and bottom plates being of equal thickness in each assembly. Duplicate tests appear to have been made and both the number of sections showing cracks in each test and the total number of cracks in all six tests for each steel composition were given in tabular form. To permit comparison with Figs. 1 and 4, the total number of cracks for each steel composition tested by Hasebe are now plotted in Fig. 5.

For both the low and high nitrogen series of steels (Tables 4 and 5 respectively), the CTS data in Fig. 5 indicate a marked increase in cracking as the aluminum content increases to about 0.01%, followed by a rapid decrease with aluminum at about 0.04 to 0.05%. Above this level, cracking appears to be relatively un-

changed, but cracking in the lower nitrogen steels is always somewhat greater than in the higher nitrogen steels.

Mines Branch Experimental Procedures and Results

Material

Two 400 lb heats of steel were made in an air induction furnace using consistent melting stock and commercial grade ferromanganese and ferrosilicon. Four ingots were poured from each heat, the first being of base composition with no aluminum addition. Aluminum was added to the furnace prior to pouring each successive ingot. The metal ingot moulds were circular, fluted, nominal diameter 5 1/2 in. with exothermic hot tops which ensured sound ingots. The ingots were cropped to a net weight of 60 lb, heated to 1232 C (2250 F) and forged to 2 1/4 in. thick slabs. The slabs were rolled to plates 1 1/8 in. thick X 5 in. wide X nominal 32 in. long, starting at 1204 C (2200 F) and finishing at approximately 927 C (1700 F). After cooling, the plates were normalized by heating to 899 C (1650 F) for 1 h and cooling in still air.

The composition of each ingot was determined; check analyses obtained on drillings from weldability test plates are given in Table 6. These steels will be referred to as the "aluminum series" steels.

Controlled Thermal Severity (CTS) Tests

The CTS test, with the specimens incorporating a gap to increase test severity and welded by low hydrogen electrodes, was selected originally (Fig. 6) for the evaluation of cracking. It was thought that the bead-on-plate test represented a rather artificial condition, whereas the CTS test related more closely to conditions which frequently occur in practice. In recent years, the CTS test has been employed considerably more frequently than the bead-on-plate test and, consequently, much useful data has been developed. Also, when welding C-Mn steels similar in composition to those in the current study, low hydrogen electrodes would normally be employed in practice rather than the cellulosic E6010 electrode specified for the bead-on-plate test.

Except for material to be used for some hot ductility studies, all of the rolled plate for each of the seven steel compositions was machined to provide six 1 3/32 in. thick X 4 X 4 in. plates. Because only a relatively small amount of material was available for each composition, and the fact that cracking in the CTS specimen is normally confined to the top plate, the 1 X 4 X 12 in. bottom plates were ma-

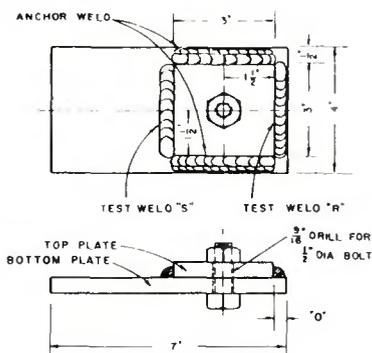


Fig. 3 — Controlled thermal severity (CTS) weldability test specimen used by Reeve (Ref. 3) and Hasebe (Ref. 4)

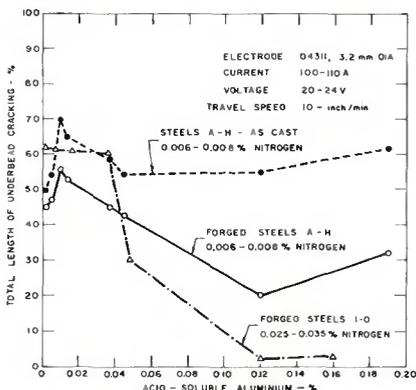


Fig. 4 — Effect of aluminum content on cracking in heat-affected zone bead-on-plate tests (Hasebe, Refs. 4 and 5)

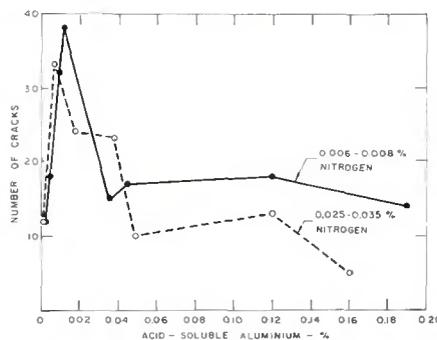
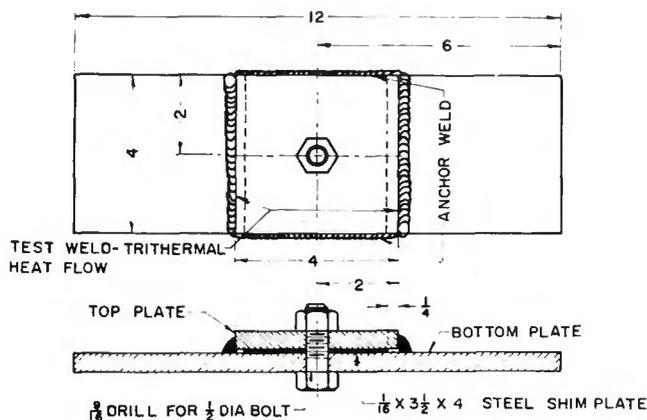


Fig. 5 — Influence of aluminum content on total number of cracks in CTS tests, plotted from data reported by Hasebe (Ref. 5) for steels shown in Tables 4 and 5, in the forged condition



CONTROLLED THERMAL SEVERITY (CTS) SPECIMENS

Fig. 6 — CTS weldability test specimen employed in Mines Branch studies

chined from a supply of commercially produced C-Mn steel conforming to either CSA G40.8 Grade A or Grade B. All surfaces against which weld metal was to be deposited, as well as the contacting surfaces of the bottom and shim plates, were ground. The upper surface of the top plate was left with the scale from rolling and normalizing in place, but the lower surface had been prepared by removal of 1/32 in. from the scaled surface. Two specimens were welded for each steel composition.

The anchor and test welds were made by 5/32 in. E7018 electrodes whose coatings contained 0.5% moisture. Test welds were deposited at an energy input close to 33,000 joules/in. and with the specimens at about 21 C (70 F). Sufficient time elapsed between deposition of the two test welds for the specimen to regain this temperature. The anchor welds were deposited using a higher energy input as assurance against possible cracking.

More than 48 h after welding, each test weld was sectioned at three equally spaced locations and all of the exposed surfaces in each specimen were examined by the wet, fluorescent, magnetic particle process. Additionally, a number of sections were subjected to metallographic examination to confirm the magnetic particle inspection results and to permit observation of the microstructures in the heat-affected zones.

Only two of the sections examined by the magnetic particle process were cracked. The two cracked sections were adjacent to each other, i.e., the surfaces examined were not more than 1/8 in. apart, and from one of the four test welds in steel A2. Microscopic examination indicated that the cracks occurred at an elevated temperature, initiating in the heat-affected zone and traveling in an intergranular path in this zone for a dis-

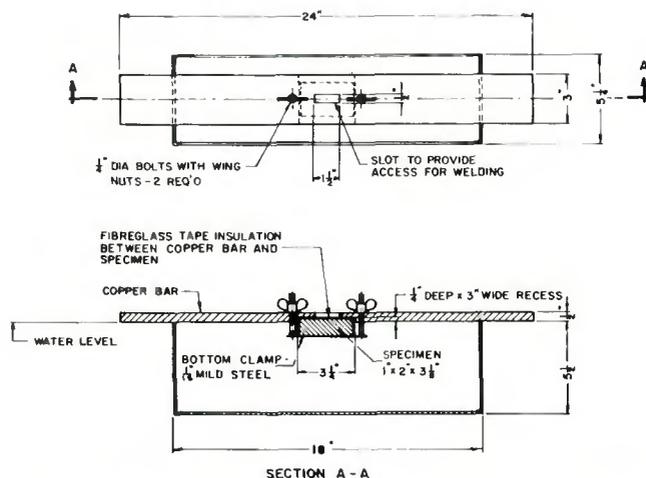


Fig. 7 — Assembly for bead-on-plate tests on the "aluminum series" steels, except for steel B1 (Table 6)

Table 4 — Chemical Analysis (wt %) of Steels Used by Haseba (Ref. 5) — Lower Nitrogen Series

Steel	C	Mn	P	S	Si	Al ^(a)	Total N	Carbon equiv. ^(b)
A	0.20	1.34	0.014	0.009	0.24	0.002	0.007	0.42
B	0.19	1.34	0.015	0.036	0.30	0.005	0.008	0.41
C	0.19	1.43	0.014	0.018	0.31	0.010	0.008	0.43
D	0.19	1.45	0.015	0.020	0.33	0.012	0.007	0.43
E	0.20	1.34	0.015	0.038	0.30	0.036	0.007	0.43
F	0.17	1.44	0.012	0.018	0.31	0.045	0.008	0.41
G	0.20	1.37	0.013	0.035	0.24	0.12	0.006	0.43
H	0.20	1.46	0.014	0.033	0.37	0.19	0.006	0.44

(a) Acid-soluble aluminum content
(b) % C + % Mn/6

Table 5 — Chemical Analysis (wt %) of Steels Used by Haseba (Ref. 5) — Higher Nitrogen Series

Steel	C	Mn	P	S	Si	Al ^(a)	Total N	Carbon equiv. ^(b)
I	0.20	1.34	0.012	0.025	0.37	0.001	0.035	0.42
J	0.20	1.32	0.012	0.024	0.32	0.007	0.031	0.41
K	0.19	1.30	0.011	0.023	0.27	0.018	0.025	0.41
L	0.20	1.39	0.012	0.025	0.29	0.038	0.026	0.43
M	0.20	1.34	0.012	0.029	0.30	0.049	0.033	0.42
N	0.21	1.32	0.014	0.035	0.28	0.12	0.034	0.43
O	0.20	1.39	0.013	0.029	0.32	0.16	0.033	0.43

(a) Acid-soluble aluminum content
(b) % C + % Mn/6

tance of about 1/8 in., i.e., equivalent to about 50% of the length of the weld fusion line shown by the section. The heat-affected zone microstructure was classified as a coarse bainite close to the fusion line where cracking was found. There was no evidence of any decarburization or oxidation on the lower surface of the top plate, thus confirming that sufficient metal had been removed from the rolled surface in preparing the specimens.

As the CTS tests failed to show any significant cracking and thus indicated that aluminum in the range studied had no effect upon the cracking tendency, it was decided to undertake some tests using a more rigid

CTS assembly. By increasing the rigidity, the restraint imposed upon the weld would also be increased and this would be expected to increase the tendency for cracking. Tests were made using a 1 in. thick commercially produced C-Mn steel (Table 6). The tests were similar in all respects to those conducted on the seven steels in the "aluminum series" except that increased rigidity was obtained by welding a 1 x 4 x 12 in. plate, which was positioned at right angles to the under surface of the bottom plate, along the longitudinal axis of this plate to form a T-shaped assembly. Two specimens were tested and no cracking occurred at the four test

welds. The steel used in these tests had a carbon equivalent of 0.44%, which is similar to that of the steels of the "aluminum series" (Table 6). It was concluded that the modified specimen, welded with low hydrogen electrodes, would not be useful in evaluating cracking in further tests on steels of the "aluminum series".

Greater susceptibility for cracking would also be expected if CTS assemblies were welded with electrodes which develop considerably more hydrogen in the arc atmosphere than that produced by the E7018 electrodes. Therefore, using the commercially produced C-Mn steel (as was used for the specimens modified to increase restraint) CTS tests were made on standard specimens in 1 in. plate (Fig. 6) welded at 33000 to 34000 joules/in. but with either E7014 or E6010 electrodes. Thus, except for the electrodes and the steel, these tests were similar in all respects to the earlier tests on the steels of the "aluminum series". Coating moisture values of 3.5% for the E7014 electrodes and 12.3% for the E6010 electrodes were reported. No cracking was found at the test welds in two specimens welded with E7014 electrodes despite the presence of a significantly greater amount of moisture as compared to the E7018 electrodes (3.5% vs 0.5%) which were used in the CTS tests on the steels in the "aluminum series". Thus there was no advantage in using E7014 electrodes in further CTS studies of the steels in the "aluminum series". Considerable cracking did occur in the heat-affected zones of the test welds in two specimens welded with E6010 electrodes. However, the cracks were discontinuous and overlapping, and it appeared that it would be considerably more difficult to make an accurate estimate of the percentage of cracking than in the case of bead-on-plate specimens.

Bead-on-Plate Tests

As additional evaluation employing the CTS test did not appear to be useful, it was decided to employ the

bead-on-plate test, with E6010 electrodes, for further work on steels in the "aluminum series". With this test it would be easier to obtain a more accurate quantitative estimate of the extent of cracking. It was also thought that an evaluation of these steels using the bead-on-plate test would permit a more direct comparison with the work of other investigators such as Sims and Banta (Ref. 1), Reeve (Ref. 3) and Hasebe (Refs. 4 and 5).

The four remaining unwelded CTS top plates in each of the steels (Table 6) were machined to provide eight 1 in. thick \times 2 \times 3 1/8 in. specimens for each steel composition. The plate rolling direction was parallel to the 3 1/8 in. dimension. This dimension was made 1/8 in. longer than that normally employed in order to compensate for the loss of metal due to the 1/2 in. bolt hole that had been drilled in each of the CTS top plates. The 2 \times 3 1/8 in. surfaces were each prepared by grinding to 1/16 in. below the original rolled plate surfaces and thus any surface effects from hot working or normalizing were eliminated.

In the bead-on-plate test, it is necessary to support the specimen so that its upper surface is 1/4 in. above the level of the liquid in the bath and to provide an electrical ground connection to the specimen. In all tests on steels of the "aluminum series", except for steel B1 which was tested later, the specimen was clamped to the underside of a copper bar in a recess as shown in Fig. 7. Several layers of fiberglass tape were placed on the surface of the recess in order to provide some measure of thermal insulation between the bar and the specimen. The specimen was clamped into the recess by means of a strip of 1/16 in. thick steel which was tightened against the lower surface of the specimen. A centrally positioned slot through the bar provided access for depositing a weld bead, 1 1/4 in. in length, on the top surface of the specimen. The copper bar carrying the specimen was supported on the top of a box which was filled with water at 21 C (70 F) until a slow over-

flow occurred.

The test welds were deposited with 1/8 in. E6010 electrodes and the welding procedure was specified to be 100 A, 24-26 V and 10 in./min travel speed. About one minute after completion of welding, each specimen was removed from the bath and stored at room temperature for at least 24 h prior to tempering at 593 C (1100 F) for 1 h.

A section from each specimen, coincident with the longitudinal axis of the weld, was prepared by cutting with a liquid cooled abrasive cut-off wheel. The total length of cracking was measured in the heat-affected zone of each specimen after delineation of cracking was accomplished by fluorescent, magnetic particle inspection. When cracks overlapped, the length of the overlapping portions was counted as one crack length. Average cracking for each of the steels was calculated from the total crack length in each set of eight specimens as a percentage of the total weld length in each set. The results are given in Fig. 8, together with results of Sims and Banta (Ref. 1) and of Hasebe (Ref. 4) for comparison.

The method or procedure used in conducting the Mines Branch tests was subsequently re-examined. It seemed possible that variations in the way the test was conducted by different investigators might account for different conclusions on the effect of aluminum. Literature references to the bead-on-plate test omit details such as how the specimen was held in the bath while providing an electrical ground connection.

Certain factors in the method used for the tests on the steels of the "aluminum series" now appeared to represent departures from a "standard" test procedure such as may have been used by other investigators. With the method used for the steels of the "aluminum series", except for steel B1, subsequent observations showed that positioning a 3 1/8 in. long specimen in a 3 1/4 in. slot in the copper bar, while the bottom surface of the bar was just in con-

Table 6 — Composition (wt %) of Steels Used at Mines Branch in this Study

Code no. (a)	C	Mn	P	S	Si	Al (b)	Total Al	Al (c)	Total N	Carbon equiv. (d)
B1	0.20	1.49	0.010	0.017	0.31	—	<0.002	0.001	0.008	0.45
A3	0.20	1.60	0.010	0.025	0.26	0.005	0.009	0.010	0.011	0.47
A4	0.20	1.55	0.010	0.027	0.26	0.008	0.013	0.015	0.010	0.46
A2	0.20	1.58	0.010	0.025	0.27	0.012	0.013	—	0.011	0.46
B2	0.20	1.49	0.010	0.018	0.31	0.040	0.047	0.050	0.009	0.45
B3	0.19	1.49	0.010	0.021	0.31	0.064	0.066	0.081	0.009	0.44
B4	0.19	1.49	0.010	0.021	0.31	0.137	0.146	0.160	0.009	0.44
Com. Steel	0.22	1.32	0.006	0.021	0.20	—	0.025	—	0.005	0.44

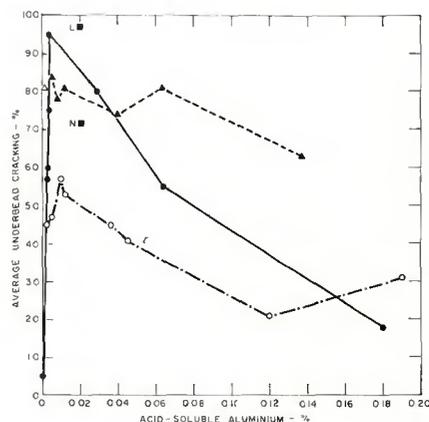
(a) A2, A3 and A4 from one split heat. B1, B2, B3, B4 from another; all referred to as "aluminum series" steels
 (b) Acid-soluble aluminum content

(c) Aluminum determined spectrographically
 (d) % C + % Mn/6

CODE	RESEARCHER	STEEL COMPOSITION	TEST TEMP °C (°F)	OTHER
●—●	SIMS & BANTA	TABLE 1	-18 (0)	
○—○	HASEBE	TABLE 4	21 (70)	MOST PROBABLE TEMP
▲—▲	CAMPBELL	TABLE 6	21 (70)	BEFORE MODIFICATION OF TEST PROCEDURE
Δ	CAMPBELL	TABLE 6 - STEEL B1	-17 (1)	WITH MODIFIED TEST PROCEDURE
L ■	CAMPBELL	TABLE 6 - COMMERCIAL STEEL	-14 (7)	WITH MODIFIED TEST PROCEDURE
N ■	CAMPBELL	TABLE 6 - COMMERCIAL STEEL	21 (70)	WITH MODIFIED TEST PROCEDURE

(DATA OF SIMS AND BANTA REPLOTTED TO DIFFERENT HORIZONTAL SCALE FROM ORIGINAL)

Fig. 8 — Average underbead cracking on bead-on-plate tests on C-Mn steels found by Sims and Banta (Ref. 1), Hasebe (Refs. 4,5) and Campbell



tact with the water, caused the water to rise, by surface tension forces, towards the top of the specimen in the 1/16 in. gap between the ends of the specimen and the slot. Heat extraction from the specimen into the water would be expected to be increased as compared to the "standard" condition. This was readily corrected by increasing the length of the slot and thus preventing capillary action at the ends of the specimen. However, it was thought that greater heat extraction, as compared to "standard" conditions, could also occur because of heat flow through the glass tape into the copper bar. The efficiency of the bar as a heat sink would have been further increased by the fact that the bar was in contact with the water.

Consequently, the method was modified by inverting the copper bar, inserting a 1/8 in. thick transite piece between the bar and the specimen, and supporting the bar above the water level on two leveling screws at each end. When the tank was filled to overflowing, the leveling screws were adjusted so that the specimen was immersed to 1/4 in. from its upper surface. With this condition, the bottom surface of the copper bar was 3/8 in. above the water level. Thus, subsequent control of the water level on the specimen was easily maintained and excessive cooling through the copper bar was avoided. A minor modification was that the slot in the copper bar was increased to 3/8 x 1 1/4 in. to provide additional assurance that weld metal would not be deposited against the bar.

Prior to carrying out further work using the modified procedure, some trial tests were made to establish the correct welding conditions. These tests showed that it was now not possible to deposit beads with any of several recently purchased brands of 1/8 in. E6010 electrodes at an arc voltage of 24 to 26 as recommended (Ref. 2) for the "standard" procedure. The arc voltage was always in the range of 27 to 32 V. The voltage measuring equipment and connections were checked and no errors in

equipment or measuring techniques were found. Voltage leads were connected directly to the electrode holder and the copper block and voltages were read on a newly calibrated meter. Thus, in order to deposit welds at an energy input of 15000 joules/in., which would result if the "standard" procedure was employed, the welding current and speed of travel were changed from the "standard conditions" to compensate for the increased arc voltage. The test specimens were welded at 60 to 70 A, 27 to 32 V and 6.4 to 8.2 in./min travel speed. These figures represent the range of conditions for welding 23 specimens, not the much smaller range of conditions for welding individual specimens. A recording wattmeter was used, and trial runs were made to achieve an energy input close to 15000 joules/in. The energy input was calculated from the product of the average wattage and welding time divided by the 1.25 in. weld length.

Employing the modified procedure, two series of tests were made on 1 x 2 x 3 in. specimens machined from the commercially produced C-Mn steel (Table 6). One series was welded with the specimens in water at 21 C (70 F) which was overflowing very slowly from the bath. Attempts were made to use a mixture of ethylene glycol, water and dry ice to cool specimens to -18 C (0 F) prior to welding. This was abandoned when it was noted that moisture was condensing on the surface of the specimen and the copper bar. Consequently, the equipment was transferred to a cold room and the entire apparatus and all specimens were cooled down (without dry ice being used) to a bath temperature of -14 C (7 F). The specimen was still immersed to a level 1/4 in. from its top surface in the liquid bath, but there was no overflow of the liquid from the bath. For both test series, the specimens remained in the bath for one minute after completion of welding. Specimens welded at -14 C (7 F) were left for up to 24 h at the ambient

temperature prevailing in the cold room (close to -14 C (7 F) and then for more than 24 h at normal ambient temperatures prior to tempering for 1 h at 593 C (1100 F). Specimens welded at 21 C (70 F) were held for more than 24 h at normal ambient temperature prior to tempering. All specimens were then examined for cracking as for the steels of the "aluminum series". Only specimens in which the welding energy input was between 14000 and 17000 joules/in. were included in the evaluation. The average energy input was close to 15000 joules/in. for each of the two series of tests. The average cracking was 72% for 11 tests at 21 C (70 F) and 97% for 10 tests at -14 C (7 F). The length of cracking in specimens within each series was quite consistent.

The specimens of steel B1 of the "aluminum series" were then welded in a similar fashion in the cold room but at a temperature of -17 C (1 F). Energy input was in the range of 15000 to 16000 joules/in. After similar post-weld handling and examination for cracking, the average cracking for the eight tests was determined to be 81%.

Discussion

A comparison of bead-on-plate results obtained by Sims and Banta, Hasebe, and the author, are given in Fig. 8. The nitrogen contents of the steels tested by Sims and Banta were not determined, but Hasebe's steels contained 0.006 to 0.008%, and the author's "aluminum series" steels contained 0.008 to 0.011%. The commercial C-Mn steel, also tested by the author, contained 0.005% N. As indicated by Hasebe (Fig. 4), the nitrogen content appears to have a significant effect upon cracking. Possibly, variations in nitrogen content in the steels tested by Sims and Banta have influenced the results obtained. This may be one of the factors referred to by these authors in their statement that the effect of aluminum upon cracking depends upon other factors

as well.

Sims and Banta's data indicate a marked, rapid increase in cracking as the acid-soluble aluminum content increases from nil to " $<0.0035\%$ " followed by a more gradual but marked reduction in cracking at higher levels of aluminum.

Hasebe's data show only a relatively small increase, i.e., about 10% in cracking as the aluminum content increases from 0.002 to 0.01% followed by a gradual decrease in cracking, smaller than that reported by Sims and Banta, at higher aluminum contents. Cracking in Hasebe's tests was always significantly less than that reported by Sims and Banta except at the lowest and highest aluminum contents. A partial explanation for the generally greater cracking found by Sims and Banta may relate to differences in the temperature of the specimen and cooling bath. Their tests were done at -18 C (0 F). Hasebe's test temperature was not stated but presumably was about 21 C (60 F) as this is normally employed, according to Stout and Doty (Ref. 2). As shown by the author's tests on the commercial grade steel (Fig. 8) greater cracking can be expected to occur at the lower test temperatures.

The author's results for the "aluminum series" steels, in tests made at 21 C (70 F) prior to modification of the bead-on-plate test procedure, showed fairly uniform cracking ranging from 74 to 84% over the aluminum range 0.005 and 0.064%. Between 0.005 and 0.04% Al, the author's results are closer to those of Sims and Banta than to those of Hasebe. Judging from the increased cracking which occurred in the author's commercial C-Mn steel at the lower test temperature, the degree of agreement between Sims and Banta's results and those for the author's "aluminum series" would not be expected due to the different test temperatures employed. It might be argued that the procedure employed for most of the "aluminum series" steels, even though at a test temperature of 21 C (70 F), resulted in cooling rates equivalent to those in tests done by Sims and Banta at -18 C (0 F) due to differences in specimen support in the liquid bath. This view is compatible for test results on steels with aluminum in the range 0.005 to 0.04%. However, it is not supported by the fact that much greater cracking occurred in the author's tests on steels with aluminum levels above 0.04%.

Some support for the view that very low aluminum levels are associated with reduced cracking is suggested by the tests on steel B1 ($<0.002\%$ total Al) at -17 C (1 F) and on the commercial steel (0.025% total Al) at

-14 C (7 F). Both test series were made using the modified procedure, and the steels had similar carbon equivalent values. Cracking was about 17% less in the steel with the lower aluminum content. However, this reduction in cracking was much less than that indicated by Sims and Banta, although greater than that shown by Hasebe, for similar aluminum levels. The cracking level in steel B1 is much higher than would have been predicted from Sims and Banta's data.

The cracking shown by the author's tests is always greater than that shown by Sims and Banta at levels of aluminum greater than 0.04% and by Hasebe for all levels of aluminum studied. It could be speculated that greater cracking than in Hasebe's tests would be expected in the author's tests at 21 C (70 F) prior to modification of the test procedure because the heat extraction from the specimens was probably greater than in Hasebe's tests. However, the author's tests on the commercial C-Mn steel at 21 C (70 F) were made after the procedure was modified to reduce heat extraction from the specimen and thus to utilize a more "standard" procedure. Despite this procedure modification, cracking in this steel was still high in comparison with Hasebe's results, being much closer to the results for the "aluminum series" steels which were tested prior to the modification. No explanation for this apparent anomaly is advanced.

Hasebe's bead-on-plate and CTS results in Fig. 4 and 5, respectively, are in reasonably good agreement for his lower nitrogen steels in showing an increase in cracking as aluminum increases from almost nil to about 0.01%. The increase shown by the CTS tests is more marked than that shown by the bead-on-plate studies. However, poor agreement is shown for his higher nitrogen steels. The CTS work (Fig. 5) shows a definite increase in cracking at about 0.01% aluminum, whereas the bead-on-plate work (Fig. 4) shows no change in cracking over the aluminum range 0.001 to 0.04%. It is noted also that the bead-on-plate studies indicate, in general, an increasingly greater reduction in cracking, compared to the maximum at lower levels of aluminum for steels of both nitrogen levels, as the aluminum increases; whereas the CTS studies do not show much change in cracking, beyond an aluminum level of about 0.04%. No explanation was advanced for these discrepancies.

Factors other than the aluminum content of the steels may have influenced the cracking tendency in tests done by different investigators. Reeve concluded that the aluminum

content of his steels had no effect upon cracking, despite the presence of aluminum in some of the steels being close to the level, i.e., .005 to 0.02%, indicated by Sims and Banta to cause maximum cracking susceptibility. However, it is noted that Reeve's steels (Table 3) had relatively low carbon equivalent values. For steels with aluminum in the range 0.004 to 0.013%, three had carbon equivalent values of 0.30 to 0.33% and one had a value of 0.40%. It is the author's view that the carbon equivalent values in Reeve's steels were too low to produce crack sensitive microstructures, particularly if the energy input was higher than normal for the bead-on-plate test.

An indication of the latter is given by the development of cracking in the range 8 to 28% in Reeve's bead-on-plate tests on two control steels each having a carbon equivalent value of 0.49%. The steel compositions reported were: 0.23% C, 1.55% Mn, 0.046% P, 0.051% S and 0.12% Si for one steel and 0.22% C, 1.62% Mn for the other steel. At an energy input of 15000 joules/in. in the bead-on-plate test, steels with this carbon equivalent value would be expected to show a much higher crack percentage. Nitrogen, which was shown by Hasebe to have a definite effect upon cracking in aluminum bearing steels, was not reported by Reeve, or Sims and Banta. Also, as mentioned earlier, the test temperature was shown by the author to exert a definite influence upon cracking. Even at a fixed test temperature, variations in the way the specimen is held in the liquid bath may exert an influence upon cracking, although this was not proved conclusively in the present work.

The volume of voids present, and even the cleanliness of the surfaces of the voids may have influenced the extent of cracking in the steels tested by different investigators. A reduction in the volume of voids associated with manganese sulfide inclusions has been claimed (Ref. 6) to increase cracking in C-Mn steel forgings which were quite low in sulfur and other nonmetallic impurities. With a large "void volume", hydrogen was thought to become stored in the voids and thus rendered ineffective as a cracking agent. Differences in the amount and composition of inclusions and in the temperature and extent of forging conceivably could result in marked differences in "void volumes" in the specimens tested by different investigators.

Other studies (Ref. 7) have indicated that contamination of the surfaces of voids can impede the release of hydrogen which is entrapped in the voids. In bead-on-plate tests, Hasebe found significantly greater cracking in the same steels

when cast into 1 in. plate than when forged from ingots into 1 in. plates (Fig. 4). He attributed this increased cracking in the cast material to reduced hot ductility which was thought to be caused by the formation of lines of aluminum nitride precipitates and networks of sulfide inclusions. The writer speculates that differences in "void volumes" or surface condition of the voids would also explain the differences in cracking. Possibly, the surfaces of voids in the cast steel were contaminated, even on an atomic scale, so that hydrogen, emanating from the weld deposit, could not diffuse into the voids, during the rapid thermal cycle, thus increasing the cracking tendency.

The absence of any significant cracking in the author's gapped CTS tests on the steels of the "aluminum series" and on the commercial steel indicates that none of these steels are particularly prone to cracking when welded with low hydrogen processes such as would normally be employed in practice. Cracking was not produced in the commercial steel under increased restraint conditions resulting from stiffening of the test assembly despite the fact that this steel had a composition which would be associated with an increased cracking tendency, based on the results of Hasebe and particularly Sims and Banta. It should be recalled that Hasebe's CTS work involved welding of tightly fitting assemblies (Fig. 3) with electrodes of relatively high hydrogen potential. On the one hand, the absence of a gap in the assembly made the test conditions less severe than those involved in the author's tests which employed gapped assemblies (Fig. 6). On the other hand, employing electrodes which produced large quantities of hydrogen in Hasebe's tests encouraged cracking as compared to using low hydrogen electrodes in the author's tests.

Thus, in the author's CTS studies, despite the use of a gap in all of the tests, and a more highly restrained

assembly in some of the tests on the commercial grade steel, the cracking propensity was evidently still much less with low hydrogen electrodes than when ungapped CTS assemblies were welded, as in Hasebe's work, using electrodes of much higher hydrogen potential.

Conclusions

1. The pronounced increase in cracking as aluminum is increased from very low levels, i.e., 0.002% or less, to higher levels, such as about 0.01% as found by Sims and Banta and to a lesser extent by Hasebe, has not been confirmed by Mines Branch studies. If electrodes of high hydrogen potential are employed to weld steels with very low aluminum levels, cracking may be just as severe as at higher levels of aluminum.

2. The marked reduction in cracking at aluminum levels greater than about 0.01 to 0.02%, compared to peak cracking at this level as found by Sims and Banta and to a lesser extent by Hasebe, was not confirmed by Mines Branch studies. With electrodes of high hydrogen potential, severe cracking, equivalent in extent to that at 0.01 to 0.02% Al, can persist up to at least 0.06% Al. The extent of cracking may be reduced by only about 20% (in bead-on-plate tests) at aluminum levels as high as about 0.14%.

3. The absence of any significant cracking when welding with low hydrogen electrodes in gapped CTS tests, some of which involved increased restraint, indicates that C-Mn steels, in the composition range studied, can be readily welded in construction without undue difficulty provided that low hydrogen electrodes containing normal levels of moisture content are employed together with energy input/plate temperatures suitable for the carbon and manganese contents and the plate thickness and restraint factors involved. The level of aluminum, at least in the range

<0.002 to 0.15% does not appear to be a significant factor relative to cracking tendency.

4. On the basis of the results obtained there does not appear to be any justification for a limitation on the aluminum contents used in C-Mn steels for deoxidation purposes such as was concluded by Sims and Banta and by Hasebe.

5. Experience with the bead-on-plate test suggests the need for more careful control of test variables and more complete description of test procedures in order to ensure that results obtained by different users will be based on equivalent tests.

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