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WELDING TESTS ON ALGOMA PLATE SAMPLES

by

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PHYSICAL METALLURGY DIVISION

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SUMMARY OF RESULTS

Tensile, side bend, and longitudinal bend test specimens from a butt joint in 1-in. thick "Algoma 90Y" plate, welded with AWS. E9018-B3 electrodes, met the requirements of ASME Section IX "Welding Qualifications". Transverse face bend specimens could not meet the requirements of Section IX as severe cracking occurred after sustaining a bend angle of only about 60 deg. This was attributed primarily to the overmatching of the steel by the weld deposit.

In C. T. S. weldability tests on 1-in. plate and cruciform weldability tests on ½-in. plate, difficulty in assessing heat-affected zone cracking behaviour was experienced due to severe cracking of weld deposits from E9018-B3 or MIL-11018 electrodes. A moderate preheat (200-225°F) was effective in eliminating weld metal cracking, but this preheat would be expected to eliminate also any heat-affected zone cracking which might have occurred if uncracked welds could have been obtained without preheat. Some heat-affected zone cracking occurred in the absence of weld metal cracking in weldability tests welded without preheat and with lower strength electrodes of the AWS E8018-B2 classification. Thus some preheat, or

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alternatively fairly high energy input levels, is indicated in order to ensure freedom from heat-affected zone cracking in single pass fillet welds or in long multi-run deposits. The use of E8018-B2 rather than E9018-B3 electrodes is shown to provide much better assurance against weld metal cracking.

INTRODUCTION

In a letter dated September 25, 1963 (W. P. Campbell to W. E. Creswick, Algoma Steel Corporation, Sault Ste. Marie, Ontario), a summary was given of proposed testing to be carried out at the Physical Metallurgy Division on a new high strength structural steel identified as "Algoma 90Y". In a letter dated September 30, 1963, Mr. Creswick stated that the proposed program adequately covered the field of interest of the Algoma Steel Corporation.

Three plates having respective nominal thicknesses of ½-in., 1-in., and 1½-in. had been previously submitted to the Division. These had been produced by Algoma Steel Corporation and heat-treated by Canadian Heat Treaters Limited, Richmond Hill, Ontario.

The results of chemical analyses, microscopical examination, and mechanical tests on these samples were given in Mines Branch Investigation Report IR 63-116 - "Assessment of Properties of Algoma Plate Samples". For reference, the following compositions were reported for the ½-in. and the 1-in. plates.

TABLE 1

Chemical Composition of Plate Samples

	½-in. Plate	1-in. Plate
C	0.07	0.07
Mn	0.56	0.55
Si	0.24	0.23
S	0.024	0.023
P	0.026	0.023
Ni	0.02	0.02
Cr	4.35	4.35
Mo	0.33	0.33
N	0.007	0.006
Al	0.09	0.10
B*	0.010	0.011
Cu*	0.02	0.03

*Quantitative spectrographic determination, all others by chemical analysis.

The nominal ultimate and yield strength values were 94 kpsi and 81 kpsi respectively.

The present report describes weldability tests which were carried out on the ½-in. and 1-in. plate samples.

Electrodes conforming to AWS E9018-B3 classification were selected initially for the tests, because it was thought that this electrode provided the closest match in composition and mechanical properties with the Algoma 90Y steel, that could be obtained in any commercially-available electrode.

MECHANICAL TESTS ON A BUTT WELD

A double vee butt joint was welded in the 1-in. thick plate to provide a specimen for mechanical tests across the joint. All welding was done manually using electrodes conforming to AWS class E9018-B3 (Canox brand). The two root beads were deposited with 5/32-in. diameter electrodes at about 30,000 j/in. energy input, and the six beads, made subsequently, were deposited with 3/16-in. diameter electrodes at about 40,000 j/in. energy input. Moisture determinations on coating samples representing each electrode size gave values of less than 0.20%. No preheat was used and welding proceeded without interruption except for time required in removing slag, changing electrodes or turning the plate to weld on opposite sides of the joint.

Radiographic examination of the completed weld indicated that it was of good quality. Transverse side bend specimens, transverse face bend specimens and longitudinal bend specimens were machined to a thickness of 3/8 in. and in accordance with Figures Q-7.1, Q-7.2, and Q-7.3 respectively, of ASME Section IX "Welding Qualifications" (1959 edition - amended to 1962). Standard 0.505-in. diameter transverse tensile specimens were also machined. All specimens were inspected by radiographic and magnetic particle methods and were found to be of satisfactory quality.

The bend test specimens were bent around a $1\frac{1}{2}$-in. diameter former, in accordance with the requirements of ASME Section IX, until either cracking occurred or a bend of 180 deg was sustained without cracking. Four side bend specimens and one longitudinal bend specimen were bent 180 deg without significant cracking. A second longitudinal bend specimen bent about 120 deg before a crack of 1-in. length formed on the tension face, apparently starting at a small weld defect. The transverse bend specimens were bent so that the surfaces closest to the weld face were in tension i.e. face bend specimens. All four specimens cracked completely across the tension faces, apparently near the outer boundary of the heat-affected zone, after being bent about 60 deg. It was evident from the appearance of the transverse side bend and the transverse face bend specimens that the yield strengths of the weld deposits and a major portion of the heat-affected zones were greater than that of the base metal.

The following tensile results were obtained:

TABLE 2

Transverse Tensile Results*

UTS Kpsi	YS (0.2% Offset) Kpsi	% El in 2 in.	% RA
93.8	81.0	20.0	74.9
94.5	81.1	18.5	75.0

*From Report PM-T-63-1449 (Mechanical Testing Section, Physical Metallurgy Division).

Both specimens broke outside the middle third portion of the gauge length, about $\frac{1}{2}$ in. from the edge of the weld.

Figure 1 illustrates the mechanical test specimens.

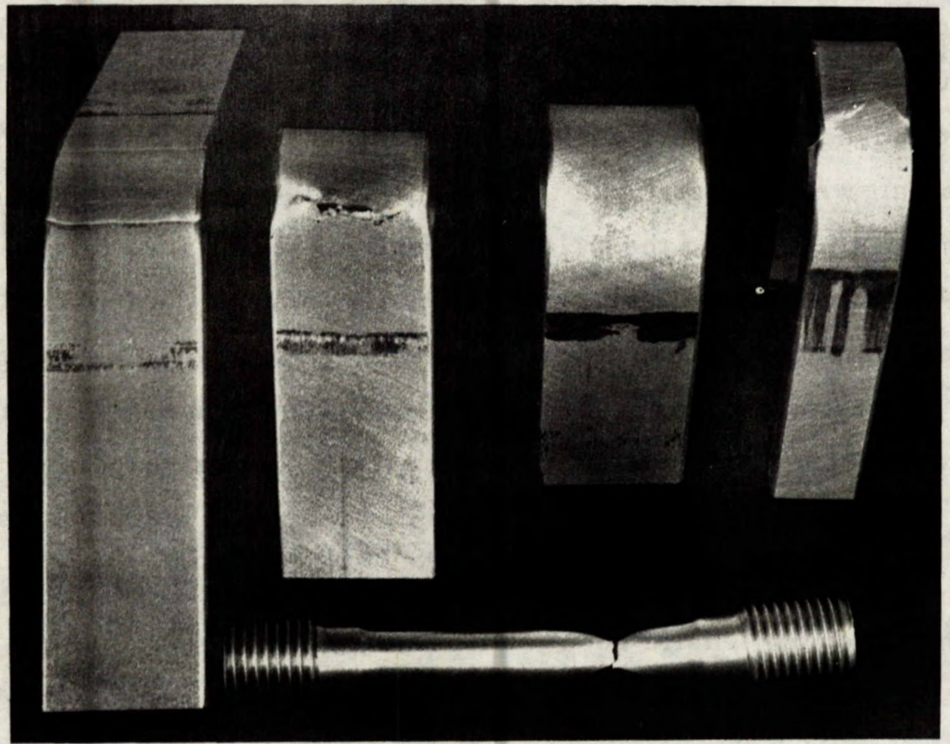

Figure 1 - Illustrating from left to right, a failed transverse face bend specimen, a failed longitudinal bend specimen, a successful longitudinal bend specimen, and a successful side bend specimen. Failure in the tensile specimen is about ½ in. from the edge of the weld.

WELDABILITY TESTS FOR ASSESSMENT OF UNDERBEAD CRACKING BEHAVIOUR

Cruciform weldability assemblies, as shown in Figure 2, were machined from the $\frac{1}{2}$-in. plate. Thickness "T" was $\frac{1}{2}$ in.

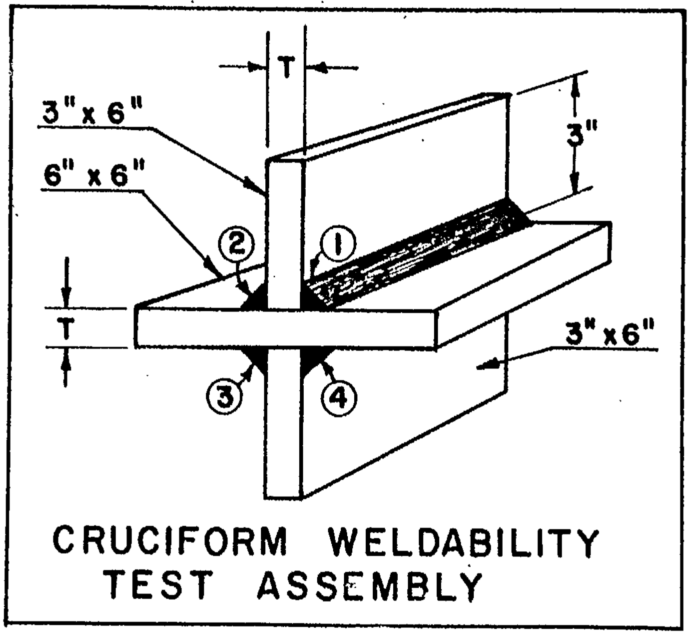

Figure 2 - Cruciform Test Assembly

Controlled Thermal Severity (C. T. S.) assemblies, having 1-in. thick top and bottom plates were machined from the 1-in. plate.

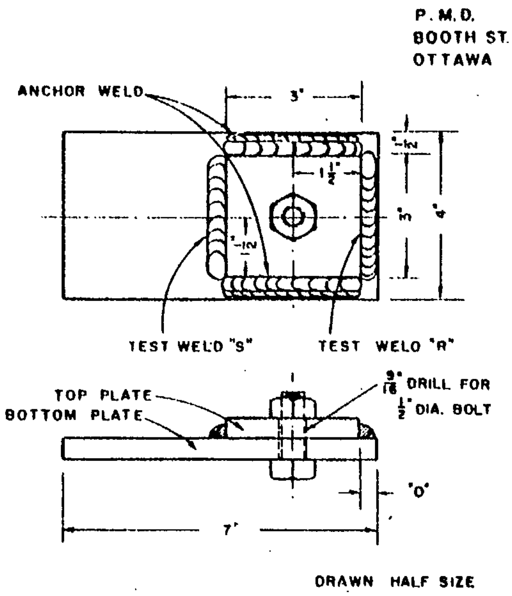

Figure 3 - Controlled Thermal Severity (C. T. S.) Test Assembly

In both test assemblies, all contacting surfaces between plates, and all areas where welds would be deposited, were provided with a ground finish.

Details of the tests are summarized in Table 3. All welding was done manually with 3/16-in. diameter coated stick electrodes. Tests were made using several different makes and classifications of electrodes because difficulty was experienced with weld metal cracking. The moisture contents of sample electrode coatings were determined using a method similar to that described in CSA Standard W48.1-1962 (Mild Steel Arc-Welding Electrodes).

All but two of the assemblies were welded without preheat. In these tests, an interval of 2 hr was maintained between deposition of subsequent welds and thus the steel temperature was about 70°F at the start of each deposition.

A preheat temperature of 200-225°F was used in two C.T.S. tests. The assemblies were heated in an oven to a temperature of 225°F. Prior to deposition of each test weld, the surfaces adjacent to the weld location were tested using temperature-indicating crayons to ensure that the metal was within the preheat range at the start of deposition.

Welds were deposited as uniformly as possible. Energy input levels, determined from traces made by a recording wattmeter, were close to 40,000 j/in. for all tests except one for which a level of about 48,000 j/in. was employed.

The test assemblies were cut by a water cooled abrasive wheel to provide sections transverse to the welds, with three sections being obtained from each of the "S" and "R" welds of the C.T.S. tests and four being obtained from the cruciform tests. These sections were examined by the magnetic particle process using an alternating magnetizing current and a liquid containing iron particles coated with a fluorescent material. Under ultra-violet light, even very fine cracks are clearly revealed. The results of these examinations are summarized in Table 3.

TABLE 3

Cruciform and C. T. S. Weldability Tests

Test No.	Type of Test	AWS Electrode Classi-fication	Elec-trode Make	Moisture Content %	Results
1	Cruciform	9018-B3	Canox	0.20	Small amount of weld cracking. No HAZ cracking.
2	"	"	"	"	Small amount of weld cracking and HAZ cracking.
3	C. T. S.	"	"	"	Severe cracking in "S" weld, none in "R" weld. No HAZ cracking.
4	"	"	"	"	Severe cracking in "S" weld, none in "R" weld. No HAZ cracking.
5	Cruciform	11018	Lincoln	0.77	Some 1/8-in. long weld metal cracks. Severe HAZ cracks below weld 3.
6	"	6012	Airco	4.7	Small amount of weld metal cracking. Severe HAZ cracks below weld 3.
8	"	11018 (Meets U.S. MIL11018 Class)	Arcos	0.20	Severe throat cracks in weld 3. No HAZ cracks.
9	"	"	"	"	As above
10	C. T. S.	"	"	"	Medium severity cracks in "S" weld, small amount of cracking in "R" weld. No HAZ cracking.
11	Cruciform	9018-B3	Atom Arc	0.10	Severe throat cracks in weld 3. No HAZ cracking.
12	C. T. S.	"	"	"	Severe throat cracks in "S" weld, none in "R" weld. No HAZ cracking.
13	"	"	"	"	As above
14*	"	"	"	"	No cracks.
15*	"	"	"	"	" "
16	C. T. S.	7016	Canox	0.66	" "
17	Cruciform	"	"	"	Slight HAZ cracking. No weld cracks.

TABLE 3 (Cont'd)

Cruciform and C. T. S. Weldability Tests

Test No.	Type of Test	AWS Electrode Classification	Electrode Make	Moisture Content %	Results
18	C. T. S.	8018-B2	Atom Arc	0.04	No cracks.
19	Cruciform	"	"	"	Slight HAZ cracking. No weld cracks.
20**	"	"	"	"	Slight to moderate HAZ cracking. No weld cracks.
21†	C. T. S.	"	"	"	No cracks.
22†	"	"	"	"	No cracks.

* Assemblies preheated to 200-225°F prior to welding.

** Energy input 48,000-50,000 j/in.

† Top and bottom plates separated by a 1/16-in. insert so that a gap of 1/16 in. was present between the two plates at the locations of the two test welds.

MICROSCOPICAL EXAMINATION AND HARDNESS TESTING OF WELDS

Several cross-sections of welds from weldability tests were examined microscopically. Weld metal cracking was mostly interdendritic and showed no positive evidence of oxidation along the edges of the crack, even at X1000. Figure 4 illustrates typical weld metal cracks at the root of a weld.

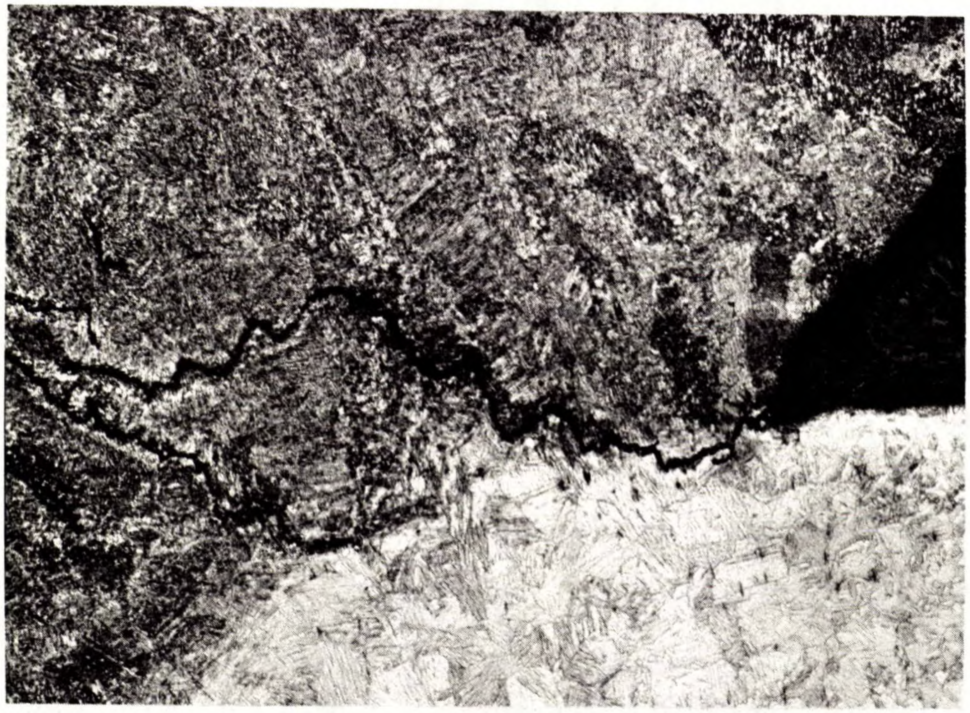

Figure 4 - Showing typical weld metal cracks near the root of a weld in a section from the "S" weld of test No. 3.
Etched 2% Nital X100

The coarse grained bainitic microstructure typical of the heat-affected zone near the weld fusion line is shown in Figure 5. Some precipitation in the grain boundaries is also apparent.

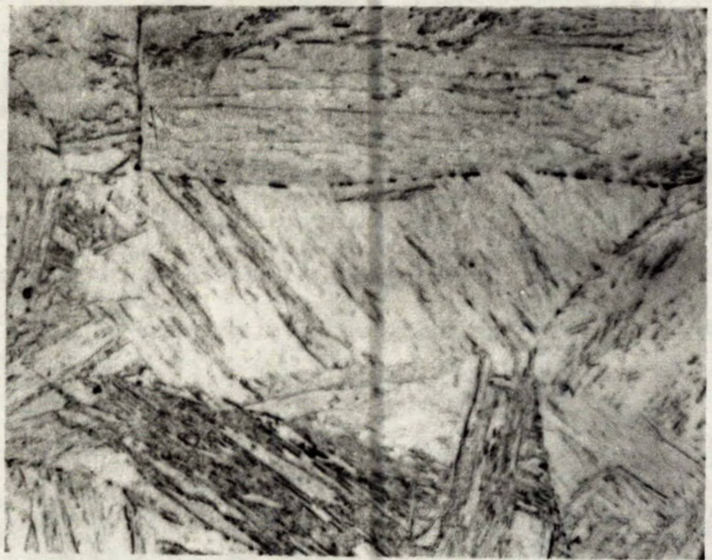

Figure 5 - Heat-affected zone microstructure close to weld fusion line in "S" weld of test No. 3.
Etched 2% Nital X1000

Hardness tests were made across the "S" weld transverse section of test No. 3, using a Tukon tester with a diamond pyramid indenter (500 g load, 4 mm objective). The values were converted to the Rockwell hardness scale. The weld deposit was 32 to 34 R_c, the heat-affected zone was 31 to 40 R_c and the base metal remote from the weld was 89 to 95 R_b. Similar values were obtained in a hardness traverse across the "R" weld transverse section of test No. 3.

A section cut from one of the transverse face bend specimens was examined. At the tension face of this section, the crack was about 1/64 in. from the outer boundary of the heat-affected zone and in metal showing no microstructural effect from welding. Considerable plastic deformation had occurred, in the region of the crack, at and close to the tension face of the specimen. There was no evidence of plastic deformation in the weld metal or the heat-affected zone at and close to the tension face.

DISCUSSION

The mechanical tests showed that the 9018-B3 weld deposits and a major portion of the weld heat-affected zone were higher in yield strength than the base metal. This could also be deduced from the relative hardness values. In the mechanical tests transverse to the weld, the weld deposit and heat-affected zones did not deform to as great an extent as the base metal, thus forcing the base metal to yield preferentially. Despite this, four side-bend specimens, one longitudinal bend specimen, and two tensile specimens met the requirements of ASME Section IX "Welding Qualifications". However, the transverse face bend specimens developed cracking after being subjected to about a 60 deg bend and thus did not meet the ASME requirements. Microscopical examination of a section from a transverse face bend specimen showed that the cracking on the tension face had been initiated just outside the outer boundary of the weld heat-affected zone and that plastic deformation was appreciable at this location, in contrast with no evidence of plastic deformation in the weld or heat-affected zone.

An unexpected difficulty was encountered in assessing the tendency for heat-affected zone cracking in the weldability tests. In most of the tests with 9018-B3 or MIL11018 electrodes, severe weld metal cracking occurred in the "S" welds of the C. T. S. tests or in the third welds of the cruciform tests. Such cracking would be expected to reduce the stress imposed upon the heat-affected zone, thus tending to invalidate the test. It was evident that the weld deposits from both makes of 9018-B3 electrodes and from the MIL11018 electrodes were more susceptible to cracking than the base metal under the conditions of the "S" weld in the C. T. S. test or of the third weld in the cruciform test.

Because the "R" welds in the C. T. S. tests welded with the 9018-B3 or the MIL11018 electrodes were uncracked, it was possible to conclude that the "R" weld heat-affected zones were not liable to cracking under the test conditions i.e. welds deposited from these electrodes containing not over 0.2% moisture and at an energy input of about 40,000 j/in. Thus, under these test conditions, the cooling rate was insufficient to produce heat-affected zone cracking.

Initially, it was thought that the weld metal cracking might be due to the use of electrodes which were particularly susceptible to hot cracking. However, this idea was discounted when tests with other electrodes showed similar weld metal cracking. The lack of positive evidence of oxidation in the weld metal cracks, the occurrence of cracks in the "S" welds but not in the "R" welds which cool more slowly, and the elimination of cracking by the use of preheat, all indicate that the weld cracking was a form of cold rather than hot cracking. The higher strength and hence more highly alloyed electrodes, such as the 9018-B3 and the MIL11018 classes, were liable to cracking under the "S" weld conditions of the C.T.S. test or the third weld conditions of the cruciform test. It is possible that the weld composition resulting from the combination of some base metal with the higher alloy weld deposit may be more susceptible to cracking than the deposit which would result from welding on a steel of lower alloy content. However, this was not established, and it is also possible that the cooling rate conditions at the "S" weld would be sufficiently severe to cause cracking in the weld deposit from the higher alloy electrodes if there had been no pick-up of alloy from the base steel.

It is noted that the difference in cooling rates between the "S" and "R" welds was not reflected by a difference in hardness values in the weld deposit or heat-affected zones in test No. 3. This may indicate that the critical cooling rates for both the weld metal and the base metal were exceeded in the "R" welds. The tendency for cracking to occur only in the "S" weld deposit may be due to the higher content of residual hydrogen which would be expected to result from the faster cooling rate.

In test No. 5, severe heat-affected zone cracks and moderately severe weld metal cracks resulted when a cruciform test was welded with an electrode conforming to the AWS11018 classification but with a higher coating moisture content than in the 9018-B3 or the MIL11018 electrodes. This indicates that an increase of coating moisture content from about 0.2% to about 0.8% will result in severe underbead cracking when a high strength electrode is used at about 40,000 j/in.

In test No. 6, severe heat-affected zone cracking and a small amount of weld metal cracking resulted when a relatively low strength electrode with high coating moisture content was used in a cruciform test. The results indicate that weld deposits from lower strength electrodes are less likely to crack than are deposits from higher strength electrodes such as the 9018-B3 or the 11018 types. However, it is evident that severe heat-affected zone cracking can be expected if the lower strength electrode contains appreciable moisture in the coating. In tests No. 16 and 17, no weld metal cracking resulted in either test and only slight heat-affected zone cracking resulted in the cruciform test when deposits were made from 7016 electrodes containing about 0.7% moisture in the coating. These two tests confirm the observation that lower strength weld deposits are less liable to cracking under the test conditions. It may also be concluded that with a coating moisture level of about 0.7 to 0.8%, heat-affected zone cracking is more liable to occur with the higher strength electrode (test No. 5) than with the lower strength electrode (test No. 17). Presumably, this is because the lower strength deposit yields and reduces the stress imposed on the heat-affected zone.

A comparison of tests No. 12 and 13 with tests No. 14 and 15 indicates that a moderate preheat of 200-225°F is effective in eliminating weld metal cracking in C.T.S. tests welded with one of the 9018-B3 electrodes at 40,000 j/in.

Some additional tests were made using 8018-B2 electrodes because it was thought that the strength level of this class of electrode would match the base metal strength level more closely than would the electrodes which had been used in the other tests. No weld metal cracking was found, thus indicating again that the lower strength, lower-alloy weld metal is less likely to crack in either the cruciform or C. T. S. tests. It cannot be concluded that higher energy input levels, i. e. 50, 000 rather than 40, 000 j/in., will eliminate heat-affected zone cracking entirely with this electrode, as slight to moderate cracking was present in test No. 20. It was rather surprising to find cracking at this energy input level when the electrode coating was very low (0. 04%) in moisture. Tests No. 21 and 22 were similar to test No. 18 except that the top and bottom plates were separated by 1/16 in. thick steel inserts so that a 1/16-in. gap was present at the two test welds. According to work by Sutherland[(1)], such a gap increases the tendency for heat-affected zone cracking. However, with the Algoma steel, there was no evidence of heat-affected zone cracking in C. T. S. tests welded with the 8018-B2 electrodes at 40, 000 j/in. either with or without the gap.

It should be noted that no evidence of weld metal cracking was encountered in the butt weld which was produced for mechanical tests, despite the fact that this weld was made using a 9018-B3 electrode which cracked severely in C. T. S. tests. A partial explanation may be that in the butt joint, unlike the single pass weldability tests, there is both a normalizing and a tempering action of subsequent beads upon previous beads and also a preheating action of earlier beads upon subsequent beads.

CONCLUSIONS

(1) In mechanical tests on specimens machined from a butt joint in 1-in. Algoma 90Y plate welded with 9018-B3 electrodes, the transverse tensile, the transverse side bend and the longitudinal bend requirements of ASME Section IX "Welding Qualifications" were met, but the transverse face bend test requirements were not met.

(2) The deposit from the 9018-B3 electrode, and also a major portion of the weld heat-affected zone, overmatched the yield strength of the base metal, thus resulting in failure of the transverse face bend tests.

(3) A thorough assessment of the tendency for heat-affected zone cracking in tests welded without preheat and with either of the two makes of 9018-B3 electrodes or a MIL11018 electrode, at an energy input of 40,000 j/in., was not possible due to severe weld metal cracking which occurred in most of the tests. However, two cruciform tests, which showed little or no weld cracking, also showed very little heat-affected zone cracking.

(4) A greater tendency to cracking was shown by the 9018-B3 or the MIL11018 weld deposits than by the base metal heat-affected zones in both C. T. S. and cruciform weldability tests.

(5) A moderate preheat of 200-225°F was effective in eliminating weld metal cracking when C. T. S. tests were welded with a 9018-B3 electrode at 40,000 j/in. energy input. It is believed that the weld metal cracking is a form of cold cracking, rather than of hot cracking, along the columnar boundaries of the cast metal.

(6) Deposits from lower strength electrodes such as the 8018-B2 and the 7016 classifications were uncracked under weldability test conditions which caused severe cracking in higher-strength, higher-alloy deposits from 9018-B3 or MIL11018 electrodes. This observation supports the contention that weld cracking in the higher strength deposits is due to cold cracking. The 8018-B2 electrode, but not the 7016 electrode, could be considered for welding the Algoma 90Y steel if it is the intention to provide approximately matching mechanical properties.

(7) With the 8018-B2 electrode, even with very low coating moisture contents, some heat-affected zone cracking occurred in cruciform tests welded without preheat at energy input levels as high as 50,000 j/in.

Thus, some preheating, or, alternatively, higher energy input levels, would be necessary to ensure the elimination of heat-affected zone cracking in this type of test, and presumably also in fillet welded structural joints or on long multi-run butt joints where subsequent beads are not deposited with a minimum of delay.

(8) At about the same level of electrode coating moisture content, and under the same weldability test conditions, there was some indication that heat-affected zone cracking was more liable to occur with higher strength (i.e. 11018) than with lower strength (i.e. 7016) electrodes.

(9) There was some indication that heat-affected zone cracking was more liable to occur when the electrode coating moisture level was about 0.8% than when it was about 0.2%, in cruciform tests welded under the same test conditions with electrodes of the same high strength level (i.e., 11018).

REFERENCES

1. J. D. Sutherland. "Effect of Joint Gap on Cracking in High-Tensile C-Mn Steel". British Welding J. 10 (3), 71-79 (March 1963).