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COMPARISON OF NOTCH-DUCTILITY OF WELDS MADE BY VARIOUS PROCESSES IN STRUCTURAL STEELS

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PHYSICAL METALLURGY DIVISION

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COMPARISON OF NOTCH-DUCTILITY OF WELDS MADE BY VARIOUS PROCESSES IN STRUCTURAL STEELS

by

W. P. Campbell*

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ABSTRACT

Several specimens, welded by various processes/procedures in 3/4-in. thick CSA G40.8 Grade B steel, were examined by Charpy and drop-weight testing to evaluate the notch ductility at the weld centre-line. The welding processes/procedures employed were among those which are or could be employed in construction of ships and other structures.

Marked differences in notch ductility were found but there appeared to be no rational correlation between the Charpy and drop-weight results. All of the processes/procedures involving electrodes, electrode/flux, or electrode/shielding gas combinations, for which CSA or AWS specify certain Charpy requirements, were capable of meeting these requirements. More stringent Charpy requirements which have been required in naval construction were met by some of the processes/procedures. No correlation was found between notch ductility and the proportions of coarse or refined weld microstructures contained within the test bars.

Some limited bulge testing was performed which showed that good bulge performance could be obtained in the absence of significant notches on the weld or plate surface despite the fact that a relatively low order of notch ductility was indicated by Charpy impact testing.

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Direction des mines

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COMPARAISON DE DUCTILITÉ A L'ENTAILLE DE SOUDURES EFFECTUÉES SELON DIVERS PROCÉDÉS DANS LE CAS D'ACIERS DE CONSTRUCTION

par

W.P. Campbell*

RÉSUMÉ

Plusieurs éprouvettes d'acier CSA G40.8 de qualité B de trois-quarts de pouce d'épaisseur, soudées selon divers procédés et méthodes, ont été soumises au test de Charpy et à l'essai au choc afin d'évaluer la ductilité à l'entaille au centre de la soudure. Les procédés ou méthodes de soudage ont été choisis parmi ceux qui ou qui pourraient être employés en construction navale et pour d'autres genres de structures.

On a observé des différences marquées de ductilité à l'entaille mais il n'a pas semblé exister de corrélations rationnelles entre les résultats du test de Charpy et ceux de l'essai au choc. Tous les procédés ou méthodes comportant l'utilisation d'électrodes, ou des combinaisons électrode/flux ou électrode/écran de gaz et pour lesquels CSA et AWS spécifient certaines exigences relatives au test de Charpy, répondaient à ces exigences. Quelques uns des procédés répondaient aussi à des exigences plus strictes requises en construction navale. On n'a pas trouvé de corrélation entre la ductilité à l'entaille et les proportions de microstructures de soudure grossières ou fines présentées par les éprouvettes.

On a procédé à quelques tests de bombement limité et l'on a obtenu un bon comportement en l'absence d'entrailles importantes à la surface de la soudure ou de la plaque en dépit du fait que le test de Charpy indiquait une ductilité à l'entaille relativement faible.

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INTRODUCTION

The primary purpose of this study was to develop data that would permit comparison of the notch ductility of welds made by processes or procedures which are or could be employed in ship construction. As these processes or procedures could also be used in other welded fabrications, e.g., buildings, bridges, tanks, etc., the data obtained could also apply to these types of structures as well.

An arrangement[1] was made through R. M. Lamarche of the Department of National Defence, Directorate of Maritime Facilities and Resources, to have butt-welded specimens prepared at Marine Industries Limited. These specimens were made using plate supplied by the Physical Metallurgy Division (PMD). It was requested that Marine Industries employ electrodes, shielding gases or fluxes, as applicable, which were considered to be most suitable for ship construction work to RCN requirements. A number of processes or procedures were suggested to Mr. Lamarche and to Marine Industries as being suitable but the decisions as to those selected were to be made between Mr. Lamarche and Marine Industries personnel.

Subsequently, Marine Industries advised that they were unable to make electroslag welds in the plate supplied. Arrangements were then made with Union Carbide of Canada to weld samples in plate supplied by PMD using a newly-developed portable electroslag unit designed for applications such as in ship construction.

Electrogas weld samples, as well as samples welded in the flat position with E7018 electrodes, were produced at PMD.

PLATE MATERIAL

All plate employed was 3/4 in. thick and from the same heat of steel conforming to CSA G40.8 Grade B specification. Table 1 provides data on the heat analysis supplied by the steel manufacturer and on the range of composition shown by check analyses made at the Mines Branch on five plates selected at random from the steel used for welding studies, as well as data on the specification limits for this steel.

TABLE 1

Composition of Steel Used in Tests (%)

	C	Mn	Si	P	S	N
Heat Analysis	0.17	1.26	0.22	0.006	0.023	-
Plate Analyses	0.15/ 0.20	1.17/ 1.24	0.15/ 0.18	0.003/ 0.007	0.021/ 0.022	0.003/ 0.004
CSA Specification Limits Plate Analysis*	0.20 max	0.80/ 1.50	0.35 max	0.03 max	0.05 max	0.008 max

*Ladle and check analyses limits.

Plate was supplied in both the as-rolled and the normalized conditions. Normalizing was done by Canadian Heat Treaters Ltd., Richmond Hill, Ontario. Normalized plate was specified to meet a requirement of 30 ft lb Charpy V-notch at -25°F. Charpy testing was done at the PMD on four of the normalized plates selected at random from the supply. Charpy values at -25°F were found to be 50 to 85 ft lb for specimens in the longitudinal rolling direction and 18 to 27 ft lb for specimens in the transverse rolling direction. Additionally, Charpy tests were made on the as-rolled plate and the results are plotted in Figure 8. All specimens were centred at the mid-thickness of the plate and were notched perpendicular to the plate thickness.

Drop-weight tests were performed in accordance with ASTM specification E208[2] using Type P-3 specimens on two of the as-rolled and two of the normalized plates selected at random from the supply. The nil-ductility transition (NDT) temperatures were -15°F for both of the as-rolled plates and -50°F for both of the normalized plates.

WELDING PROCEDURE DATA

Details of welding procedures supplied by Marine Industries Limited and by Union Carbide of Canada, for specimens welded by these organizations, and welding procedures for specimens produced at PMD, are given in Appendix A. No preheating was employed for any specimens although for the arc-welded specimens the interpass temperature was 150 to 200°F. All specimens except those for the electrogas welds and the electroslag welds were made by assembling two pieces, each 10 x 48 in., and welding along the 48-in. length. The electrogas assemblies consisted of one 10 x 48-in. plate and one 20 x 48-in. plate, with the weld along the 48-in. length. A similar assembly was requested to be used for the electroslag welds but it is not certain that this was followed. Certain difficulties in producing these welds had occurred and it is probable that smaller assemblies were, in fact, employed. The specimens, as received, consisted of plates $7\frac{1}{2}$ to 9 in. in width welded together along the 48-in. length. In all specimens, the weld was perpendicular to the rolling direction of the plate.

PROCEDURE AND RESULTS

Radiographic Inspection of Welds

All welds were inspected by radiographic examination to ensure that test specimens were obtained only from metal free from cracks, incomplete penetration and fusion, and from any significant quantities of slag inclusions or porosity. The extent of porosity in the welds was judged to meet the Grade 1 Radiographic Standard for covered arc-welding electrodes[3] or the Radiographic Standard specified for continuous-wire electrodes[4,5,6], as applicable.

Charpy Impact Testing

Charpy V-notch blanks (10 x 10 mm specimens) were machined transverse to the welds in the as-rolled plate, except for the submerged-arc-weld sample MR9 which was in normalized plate. Charpy and drop-weight specimens were originally machined from submerged-arc-weld MR10 in as-rolled plate. However, the Charpy specimens had to be discarded due to incorrect machining, and as insufficient material remained for additional impact specimens from weld MR10, the required number of specimens were obtained from weld MR9. Macroscopic examination of samples from the two welds confirmed that similar welding procedures had been employed. The longitudinal centre-line of each blank coincided with the centre of the plate thickness. The blanks were lightly etched to show the weld outlines, and a scribe-mark was made on each blank to locate the notch so that it would be machined coincident with the vertical central axis of the weld and at right angles to the original plate surfaces. Some specimens had to be discarded because of variations in weld shape or alignment. The acceptable blanks were then notched and again lightly etched and re-examined to ensure that the notch had been correctly machined. A number of specimens had to be discarded at this stage.

Charpy transition curves were then developed from impact tests made at various temperatures. Usually at least five specimens were broken at each temperature. However, in some cases insufficient specimens were available and fewer than five specimens were tested at a given temperature. The individual energy absorption values for each specimen are indicated in Figures 1 to 7 inclusive and Figure 9. The transition curve for each weld process or procedure was made by joining the average value at each temperature. Table 2 provides data on average impact values corresponding to several temperatures of particular interest.

Drop-Weight Testing

Drop-weight specimens conforming to the requirements for Type P-3 specimens[2] were prepared transverse to the welds in the as-rolled plate. It had been planned to use the thicker P-2 specimens, but this was not possible because of the degree of distortion in many of the welded plates. Specimens were etched to permit accurate location of the notch in the crack starter bead at the centre-line of the weld being tested.

The procedure for determining the nil ductility or NDT temperature was as specified in the applicable ASTM specification[2]. NDT temperatures are superposed on the Charpy V-notch transition curves for each process or procedure. (Figures 1 to 7 inclusive and Figure 9) and are also given in Table 2 with the corresponding Charpy values. Figure 8 compares Charpy data from electrogas weld MR13 with an earlier electrogas weld.

Metallographic Examination

Photomacrographs were prepared of etched sections from unbroken drop-weight specimens, except for the electroslag weld MR16 where the section was cut from the as-welded joint, to illustrate the macrostructures of welds made by each process or procedure. The sections were etched in 2% nital and the photomacrographs were taken at approximately X3 magnification (Figures 10 to 17 inclusive). Some metallographic examination was also made at considerably greater magnification.

Explosion-Bulge Testing

Two explosion-bulge specimens (3/4 x 20 x 20 in.) were prepared for each process or procedure. The central 10-in. portion of the weld was left in the "as-welded" condition and the remaining portions of the weld were ground flush with the plate surfaces. Prior to commencing bulge testing, studies were made to determine (a) the length of time required to cool a plate from room temperature down to the test temperature, and (b) the gain in temperature of the plate after removal from the alcohol-dry ice bath until an assumed firing time $1\frac{1}{2}$ min. later. A thermocouple was welded to the bottom of a hole drilled to the central point of a 3/4 x 20 x 20-in. plate. Temperatures were plotted by a Speedomax recorder. The plate, in equilibrium with an ambient outside temperature of 62 to 70°F, was then placed in a bath of alcohol and dry ice. The bath had been cooled to 5°F below the explosion-bulge test temperature of -25°F. This amount of undercooling was equal to the gain in plate temperature which was found to occur when the plate was removed from the bath and held on a wooden rack until 45 sec. after removal from the bath and then held on the explosion-bulge die plate for a further 45 sec. It had been estimated that, in the field testing, the plate could be removed from the bath, carried to the die, and positioned on it, within about 45 sec. The remaining 45 sec. would be required to place the carboard box and explosive over the specimen, connect the detonation wires, ensure that all personnel were in a safe location, and fire the charge. In this pre-bulge testing, it was found that the plate cooled from ambient temperatures of 62 to 70°F down to -30°F in about 10 min. Parallel tests were also made on a 1-in. thick plate in preparation for testing of some high-strength steel weldments in another program. The 1-in. plate cooled to the same test temperature in about 14 min. It was decided to standardize on a cooling time of 25 min., at least for initial testing. With three cooling baths in operation, it was thought that this cooling time would permit sufficient time between shots for recording of data and preparing for the next shot. Also, the additional cooling time would ensure that plates at higher temperatures than 70°F (i.e., the maximum ambient and initial plate temperatures in the simulated tests) would be adequately cooled to the test temperature.

A cooling time of 25 min. would result in considerable time saving as compared to the period of 90 min., which was recommended in procedures[7] for bulge-testing. These recommendations were based on the use of a refrigerating chamber which apparently necessitates longer cooling times due to slower heat extraction by the air surrounding the plate.

A limited amount of bulge testing was undertaken at a facility provided by The Canadian Explosives Research Laboratories, Corkstown Road, between August 15 to 17, 1972 inclusive. The testing was terminated on orders from the Minister of the Department of Energy, Mines and Resources because of complaints received due to excessive noise levels at the Kanata townsite and on the adjacent Queensway.

Tests were conducted in accordance with recommended procedures[7], except that the plate cooling time was 25 min. and the stand-off distance was 19 3/8 in. rather than 20 in. The die had a 12-in. diameter hole with a radius of 1.5 in. on its upper edge. Specimens were placed in baths of alcohol and dry ice which were at -30°F, and dry ice was added as required to maintain this temperature. After being cooled for at least 25 min., a specimen was placed on the die and the explosive was fired 90 sec after removing the plate from the bath. The explosive was a 4-lb charge of pentolite supported on a cardboard box so that the bottom surface of the explosive was 19 3/8 in. above the face of the die. This is termed the "stand-off" distance.

After each shot, the specimen was examined for cracking and, if any occurred, the length of the longest crack was measured and the sample was photographed. The maximum thickness reduction in the plate at a point about 1½ in. from the edge of the weld, and the height of the bulge, were measured. The former was determined by use of a large U-gauge fitted with a dial micrometer. There was some uncertainty concerning the accuracy of this device at the time of the tests, but the results were subsequently substantiated by means of an ultrasonic thickness gauge having a digital read-out. This instrument provided a much faster method for measuring thickness.

In order to gain experience with the test procedure, preliminary testing was done using two explosion-bulge plates cut from a surplus submerged arc weld (MR10A) made by Marine Industries Limited in as-rolled plate. Specimen MR10AB failed in the first shot (Figure 18). A large piece was blown out completely and a crack extended into the hold-down region, i.e., the portion of the plate, beyond the bulged area, which is clamped to the die by the explosive force and thus is not subjected to plastic deformation. Chevron markings on the fracture face were observed pointing in opposite directions on either side of a metal stamp identification number, which had been placed in error by the fabricator on the test area (Figure 19). The chevrons pointed directly to the stamped letter "1", thus indicating that this had initiated the fracture. Specimen MR10AA was subjected to the first shot with a stand-off of only 14 3/4 in due to inadvertently employing a shorter box (intended for testing higher-strength steels). Despite this, no cracking occurred on this shot and a further eight shots at the correct stand-off distance were made, producing a total thickness reduction of 25% and a bulge height of 4 3/8 in. without any sign of cracking. On the ninth shot, a large piece was blown completely out of the bulge region without any crack extension into the hold-down region.

Tests were then made on two specimens from weld MR1. This was a weld made in the flat position, in normalized plate, using an Airco E7016 special electrode. No cracking occurred in specimen MR1A in three shots which produced thickness reductions of 4, 1 and 2% respectively, and a bulge height of 2 9/16 in. Failure occurred on the fourth shot (Figure 20) with cracking through the thickness of the plate extending into the hold-down region. The primary crack initiated at the weld, about 3 in. away from the apex of the bulge, and propagated outward at right angles to the weld. There was no marked irregularity on the weld contour or surface which would explain the initiation at this point. However, a small pinhole due to porosity, about 1/64 in. in depth was found here close to the edge of the weld, and the fracture ran in either direction from this point. It was observed that the weld had been ground on its surface and along its junction with the plate in the region where the porosity and fracture initiation were found. Branch cracks extended away from the primary crack but these were completely outside of the weld zone. Specimen MR1B showed no cracking in five shots which produced thickness reductions of 4, 1, 1½, 1, and 2% respectively, and a bulge height of 3 in. Further shots were curtailed due to discontinuance of the bulge-test program.

Two specimens were partially tested from weld MR5A, made in normalized plate in the flat position with the gas metal-arc process. In specimen MR5A, 4-lb explosive charges produced thickness reductions of 3½, 2 and 1% respectively, in three shots. In all tests to this time, the explosive charge was a single wafer of explosive weighing 4 lb. On the fourth shot on specimen

MR5A, the explosive charge consisted of four smaller wafers, each weighing 1 lb, piled one on top of the other. The thickness reduction on this shot was less than 1% in comparison to the previously-mentioned thickness reductions. Also, the bulge height increased by only about 1/16 in. as compared to about 5/16 in. on each of the second and third shots. No cracking occurred on this fourth shot. In specimen MR5B, the first shot, made with a single 4-lb charge, produced no cracking, a thickness reduction of about 3½% and a bulge height of 1 3/4 in. The second shot, with four 1-lb charges, piled one on the other, produced only about ½% thickness reduction with no measurable change in bulge height. A third shot, employing three 1-lb charges placed on a single layer, and a fourth 1-lb charge centrally located on top of the others, resulted in a slight increase in thickness reduction, i.e. about 1% and a bulge height increase of about 1/8 in. These tests show that a uniform system should be used for the explosives in order to carry out comparison tests on welds. A single 4-lb charge is preferable.

DISCUSSION

In examining the weld cross sections shown in Figures 8 to 17 inclusive, allowance must be made for the fact that all but the section for the electroslag weld were cut from drop-weight specimens which had been machined to a thickness of 0.62 ±0.02 in. from the 3/4-in. thick plate weldments. Thus, about 1/16 in. of metal thickness had been removed from each side of the original plate as well as the weld reinforcements.

A comparison of these etched sections with the data given in Appendix A indicates that some of the specimens were not welded entirely in accordance with the stated welding procedures. Reasonably good, or good agreement between the sections and the procedure data is indicated for specimens MR2, MR4, MR12, MR13, and MR16. The MR6 specimen (Figure 12) appears to have been welded employing five passes from the root side rather than three as given by the welding procedure data. Also, the penetration from the root side was much greater than suggested by the procedure data. The number of passes in specimens MR8 and MR10 appear to be fewer than given by the procedure data. This is particularly well illustrated by Figure 14 for specimen MR10. This shows that only one pass from each side had been made. The procedure specification called for three passes from the bevelled side, followed by back-gouging and deposition of a fourth pass from the root side, penetrating about one-third of the way through the joint.

Considerable scatter in the impact values at some temperatures is shown in Figures 1, 2, 3 and 6, corresponding to weld specimens MR2, MR4, MR6 and MR12 respectively. Less scatter is shown in Figures 4, 5, 7 and 9 corresponding to weld specimens MR8, MR9 (MR10), MR13 and MR16. For specimens from any specific joint, the scatter in impact values may be influenced primarily by variation in the microstructures which occur along the weld length. For example, specimens located at the mid-thickness of welds MR10 (same procedure as MR9), MR13 and MR16 which were welded automatically by the submerged arc, electrogas and electroslag processes respectively, showed relatively little scatter compared with all of the manually-made welds except for weld MR8. A comparison of Figures 13 and 14 shows that weld MR8 has a fairly similar bead deposition pattern to that of weld MR10. It is thought that there would be less likelihood for variations in the proportions of columnar "as-cast" and refined microstructures in individual impact specimens over a given length, in welds having only a few large beads, e.g., weld MR8 (Figure 13), than in welds having a large number of beads, particularly when deposited manually, e.g., weld MR2 (Figure 10).

It will be noted from the impact data given in Figures 1 to 7 inclusive, and in Figure 9, that in some cases the number of specimens tested was less than desirable. It had been intended to provide 5 specimens for each temperature but this was not possible due to various factors as explained earlier. It is recognized that where fewer specimens were tested, the degree of reliability of the results is lessened accordingly.

It is understood that the RCN has required a 30 ft lb Charpy V-notch energy value at -40°F for welds made by certain processes. Data given in the transition curves or in Table 2 indicate that, for the E7016 electrode, this requirement is exceeded by a wide margin for welds in the flat position (weld MR2) but may not be met for welds made in the vertical-up position (weld MR4). The flat position E7018 weld (MR12) met the requirement by a comfortable margin.

Gas metal-arc welds slightly exceeded the requirement with the E60S-3/argon-oxygen combination (weld MR6) but failed to meet the requirement with the E70T-1/CO_2 combination (weld MR8). A submerged-melt weld (MR9), an electroslag weld (MR16), and an "early" electrogas weld failed to meet the requirement by a wide margin. These three welds and the gas metal-arc weld (MR8) were the only ones that failed to meet a criterion of 30 ft lb at -25°F, also understood to have been specified, on occasion, by the RCN. An electrogas weld (MR13) made with an improved electrode and gas shielding, as compared to the "early" electrogas weld, exceeded the requirements at both -40°F and -25°F.

The electrodes or electrode/flux or electrode/shielding gas combinations, except for electrogas or electroslag welding, are required to be capable of producing welds under specified conditions which have Charpy impact values of 20 ft lb at either 0°F or -20°F. More specifically, AWS and CSA[3,4,5,6] specifications require that the two gas metal-arc electrodes* meet a requirement of 20 ft lb at 0°F and the other electrodes or electrode/flux combinations meet a requirement of 20 ft lb at -20°F, in welds made to prescribed conditions. For example, these procedures require welding 3/4-in. thick plates in the flat position using an interpass temperature of 300°F ±25°F. For the covered arc-welding electrodes (E7016 and E7018), the solid electrode (E60S-3*) and the flux-cored electrode (E70T-1), the test welds are to be made so that each weld layer is approximately 1/8 in. thick. The submerged arc weld is to be made under specific conditions of current, voltage, and travel speed.

The electrode specifications require the testing of five Charpy V-notch specimens at a prescribed temperature. The extreme high and low values are to be discarded and the average of the remaining values is to be at least 20 ft lb with no single value less than 15 ft lb.

Considering the weld specimens studied in the current project, differences in welding procedures employed from those prescribed by the AWS or CSA specifications were generally such as to favour some reduction in Charpy

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*The solid gas metal-arc electrode was purchased to an E60S-3 classification of specification AWS A5.18-65T. This classification has been replaced by an E70S-3 classification in later AWS and CSA electrode specifications. Both the 1965 specifications and the later specifications have the same impact requirements.

values. For example, in specimens MR6 and MR8, the weld passes in the central regions from which the Charpy specimens were removed were greater than 1/8 in. thick, judging from Figures 12 and 13 respectively. Also, in specimen MR10, the energy input appears to have been considerably higher than the maximum value of about 67,000 joules/in. specified[6] for preparation of submerged melt welds for qualification of electrode/flux combination. This is evident from the size of the weld passes shown in Figure 14. Also, the procedure data given in Appendix A for this specimen indicates an intention to use energy input values ranging from 62,000 to 128,000 joules/in. As only two passes were actually deposited, rather than the four indicated by the procedure data, this would also support the view that energy input levels were much higher than those specified by the electrode/flux specification[6]. With thicker or larger weld passes, less grain refinement of preceding passes is produced and, consequently, lower impact values would be expected. Despite variations such as this, all of the weld specimens, omitting the electrogas and electroslag specimens, met the requirements of the related specifications. Welds MR8 and MR10, which contained the largest weld passes, met the requirements by a much smaller margin than the other welds.

The electrogas and electroslag results may be compared, somewhat loosely, with requirements which can be specified by the AWS Structural Welding Code[8]. If impact requirements are specified, five specimens are to be cut transverse to the weld with the longitudinal centre-line of the specimen as near as practicable to a point midway between the surface of the plate and the centre of the thickness. (The position of the specimens is thus somewhat different from that in the current study where almost all specimens were centred on the plate thickness.) The extreme highest and lowest values obtained with the five specimens are to be discarded, and the minimum acceptable average value for the three remaining specimens is to be 15 ft lb at $0^{o}F$ with no value being less than 10 ft lb. Because of the differences in positioning of the Charpy specimens, a strict comparison between the results of the current work (Table 2 and Figures 7 and 9) and the requirements of the AWS Structural Welding Code is not valid. However, it is thought that the electroslag weld would only just meet this requirement. Four Charpy specimens, prepared as specified by the AWS Code were, in fact, tested and gave 11, 14, 14 and 22 ft lb, thus supporting this view. The electrogas weld made with Avacor wire would be expected to meet the requirements of the AWS Code by a considerable margin, judging from the properties obtained for the "centre-line" impact specimens.

The Charpy and drop-weight results for the electrogas weld MR13, and the drop-weight results for electrogas welds MR14 and MR15, are markedly superior to results which had been obtained earlier at PMD on welds made in 3/4-in. as-rolled steel from the same heat as in the later tests. In the earlier tests, the electrode was solid Airco A675 wire to classification E70S-3[4] and gas shielding of the weld pool was supplied only by one gas box mounted on one of the welding shoes. (The shoes are water-cooled copper blocks which press against the plate surfaces, closing the open sides of the weld joint and providing a retaining wall against which the weld pool solidifies. The shoes move upward with the welding head.) The gas flow is deflected downward to the weld pool by the shape of the gas exit slot in the gas box. In the later tests, the gas shielding was improved by the addition of a gas box to the other shoe. The improvement in notch ductility is attributed to the use of the flux-cored Avacor electrode as well as to the additional gas shielding. Both the flux core and the additional gas protection would be expected to produce welds having fewer non-metallic inclusions and thus to improve notch ductility.

In the more recent studies, Charpy and drop-weight tests were made only for the central weld position. In the earlier electrogas work, Charpy data was obtained for other weld joint locations as well. Although these data were obtained on as-rolled plate, using what are now obsolete welding conditions, it is considered that presentation of this data may still be of value. A similar technique to that described earlier in this report was employed in the preparation of Charpy specimens to obtain assurance in positioning of the notch. The Charpy transition curves (average values only) are shown in Figure 8 for the following locations:

(a) as-rolled unwelded plate.
(b) relatively fine grain metal at the weld centre-line.
(c) relatively coarse grain structure in the weld intermediate between the centre-line and the fusion line.
(d) close to the weld fusion line, as close as possible to being in the coarse grain heat-affected zone.

(e) very fine grain heat-affected zone.

Also shown for comparison in Figure 8 is the weld "centre-line" data for the more recent electrogas weld MR13.

The superior results for weld "centre-line" specimens in the later tests are clearly shown. The curves for the coarse columnar weld zone and the heat-affected zone close to the fusion line indicate a level of notch ductility generally lower than that of the as-rolled plate, but not greatly so. About one-half of the width of the heat-affected zone in the as-rolled plate has been altered by the welding cycle so that it has a very fine grain size. This zone has an extremely high level of notch-ductility, approximating that of the furnace normalized steel. It is thought that as-rolled and normalized plates would have similar heat-affected zone microstructures and notch ductility when welded with the same procedures.

It will be noted that the current study has concentrated on assessing the notch-ductility characteristics at the central regions of the welds. This approach was taken because of the difficulties involved in assessing the notch ductility in the heat-affected zones which are generally irregularly shaped.

In the case of electroslag and electrogas welds, the relatively straight pattern of the heat-affected zone does permit a more ready evaluation of notch-ductility in this zone. The Charpy testing in this zone of the early electrogas weld indicates (Figure 8) both some impairment close to the weld fusion line, where grain coarsening would be expected to cause greatest deterioration, as well as a marked improvement in notch ductility in the fine grain zone farther from the weld; in both cases the notch ductility is compared to that of the as-rolled plate. It is observed, also, that the Charpy curve for the coarse grain heat-affected zone indicates generally better notch ductility than the weld centre-line Charpy curves for the submerged arc weld MR9 (Figure 5) or the electroslag weld MR16 (Figure 9), and approximates the curve for the gas-metal-arc weld MR8 (Figure 4).

There appears to be no rational correlation for the various weld specimens between the average level of absorbed energy in the Charpy tests and the NDT value (see Table 2). For example, MR4 and MR9/MR10 welds had the same NDT temperature of -30°F but the average Charpy values at this temperature were 40 ft lb for the first and only 12 ft lb for the second. Also, welds MR8 and MR12 had NDT temperatures of -50°F, whereas the average Charpy values at this temperature were 14 and 37 ft lb respectively. In comparison, specimen MR6 had an NDT of -20°F with average Charpy values of 61 ft lb.

Comparing the macrostructures of welds MR4 and MR9/MR10 (Figures 11 and 14 respectively), the lower Charpy values for MR9/MR10 might be attributed to the smaller amount of fine-grained metal that would be present in the Charpy specimens as compared to those from weld MR4. However, though weld MR4 contains a considerably higher proportion of fine-grained metal throughout the drop-weight specimen, whereas weld MR9/MR10 consists mainly of coarse-grained metal, yet both welds have the same NDT temperature, it is evident that the difference in notch ductility cannot be explained solely on the basis of the relative amounts of refined and unrefined microstructures indicated in the macrosections. This is also evident in weld MR6 (Figure 12). Although Charpy specimens would include a considerable amount of unrefined microstructures, an average energy value of 61 ft lb at the NDT temperature of -20°F was obtained.

Only limited examination of microstructures at higher magnifications was undertaken. This was insufficient to provide any clear understanding of relationships between microstructure and notch ductility in the various welds. It is thought that considerable additional work would be required to achieve this and that this is beyond the intended scope of the project. However, it should be recorded that Australian investigators[9] report that submerged arc-weld metal microstructures correlate well with drop-weight NDT results.

It should be noted that the Charpy and drop-weight data obtained in the current study apply only to welds made with the same procedures and consumables. In fact, modifications in energy input and/or bead sequence, even with the same consumables, would be expected to result in some change in notch ductility from that found in the current study.

The limited amount of bulge testing precludes any significant comparison of the bulge performance of the various welds. However, even this limited work has produced some interesting results. It is evident that considerably different performance may be shown by two specimens cut from the same weld, depending upon the severity of notches in the bulge region. An extreme illustration is given by the performance of the two submerged-arc-weld specimens. Complete failure on the first shot occurred in specimen MR10AB as a result of brittle fracture initiating from the identification letters stamped by the fabricator in the bulge region. The companion specimen MR10AA withstood eight shots and a thickness reduction of 25% without failure. No stamp mark had been made in the bulge region and evidently the weld was free from any notches or defects of significance. The importance of avoiding notches on plate and weld surfaces for structures where a high order of ductility is required is well illustrated by this experience.

In view of the excellent performance of the submerged-arc-weld sample MR10AA, and the unbroken behaviour of sample MR1B, it was surprising that the E7016 weld sample MR1A failed after being subjected to a smaller amount of deformation. Even better bulge performance than for the submerged-arc weld would be predicted for the E7016 weld on the basis of the transition curves and NDT data for the two welds, i.e., Figures 1 and 5. Additionally, the submerged-arc weld was in as-rolled plate, whereas the E7016 was in normalized plate, which had considerably better notch ductility than the as-rolled plate. One possible explanation is that the automatically-made submerged-arc weld had a more regular external surface than the manually-made E7016 weld and thus provided less severe initiators for cracking. A more likely explanation is that the small weld defect (porosity) found at the point of fracture initiation in the E7016 weld provided sufficient stress concentration to initiate cracking despite the superior notch ductility of this weld indicated by Charpy and drop-weight tests. The fact that the fracture pattern in this bulge sample was off-centre indicates the presence of some defect not found elsewhere in the bulge region. It is also interesting to note that the defect was well within acceptable limits as judged by the radiographic inspection made prior to bulge testing.

Some bulge testing had been performed in the earlier electrogas work on specimens welded with an A675 electrode and a procedure corresponding to that employed for specimens from which the data in Figure 8 was developed. Figure 21 illustrates a specimen in as-rolled 40.8 Grade B steel from the same heat as used in the current study. This specimen withstood five shots at $-36^{o}F$ with no sign of cracking. Thickness reduction was about 8% and bulge height was 2 7/16 in. Probably the relatively smooth surface of the weld was an important factor in preventing fracture initiation. No further testing was done on this specimen. Judging from the excellent performance at $-25^{o}F$ of the submerged-arc sample MR10AA, also in as-rolled steel, it is speculated that further testing of the early electrogas weld would show some additional bulging and thickness reduction before development of cracking. Even better performance would be expected if the more recent electrogas welds were bulge tested, in view of their markedly superior Charpy and drop-weight performance as compared to the early electrogas welds.

CONCLUSIONS

(1) Some of the weld specimens were not prepared in accordance with the welding procedure data supplied for these specimens.

(2) The least scatter in Charpy impact results was exhibited by welds produced by the electrogas, electroslag, and submerged-arc processes and a gas-metal-arc process involving the use of a flux-cored E70T-1 electrode and carbon-dioxide shielding. Greatest scatter was found for welds made with E7016 or E7018 electrodes and for a gas-metal-arc process using a solid E60S-3 electrode and argon-oxygen shielding.

(3) The consumables and procedures employed for the flat position E7016 and E7018 welds MR2 and MR12 respectively, the gas-metal-arc weld MR6, and the electrogas weld MR13, will permit producing welds which exceed Charpy V-notch weld centre-line requirements of 30 ft lb at $-25^{o}F$ and at $-40^{o}F$. The procedure for the vertical position E7016 weld MR4 will permit meeting the requirement at $-25^{o}F$ but is borderline at $-40^{o}F$. All of the other combinations of consumables and procedures appear to be inadequate to permit meeting the requirements at either $-40^{o}F$ or $-25^{o}F$.

(4) Despite deviations from the procedures specified by CSA or AWS electrode codes, all electrodes, electrode/flux or electrode/shielding gas combinations, excluding those for electrogas or electroslag, were indicated to be capable of meeting the Charpy requirements of these specifications at either $0^{o}F$ or $-20^{o}F$ as applicable. The electrogas process/procedure using Avacor wire and good shielding appears to be capable of meeting the Charpy requirements of the AWS Structural Welding Code. The electroslag

process/procedure appears to be borderline in meeting this requirement.

(5) In electrogas welding, improvements in gas shielding and the use of an Avacor flux-cored electrode, resulted in marked improvement in notch ductility as compared to welds produced earlier using less effective gas shielding and an A675 (E60S-3) solid wire electrode.

(6) A change in procedure from flat to vertical-up position manual welding may cause a definite reduction in the notch ductility as illustrated by the Charpy and drop-weight results for welds made with the E7016 electrode.

(7) The differences in weld notch ductility shown by Charpy and drop-weight testing for the various processes must be associated with differences involving microstructures, solid solution effects, or weld cleanliness because weld surface irregularities were excluded in the notch-ductility specimens. However, weld surface irregularities could be an important factor under certain service conditions or in bulge testing of as-welded joints. Cracking could initiate at the surface irregularity providing greatest stress concentration.

(8) The differences in notch ducility associated with the various processes or procedures could not be correlated with differences in the proportions of coarse and refined microstructures in the welds.

(9) No rational correlation was evident between the Charpy values corresponding to the NDT temperatures for the various welds.

(10) Except for the early electrogas weld, all processes or procedures are capable of developing NDT temperatures, at a weld centre-line location, that are lower than a value of -15°F which was found for the particular heat of CSA G40.8 Grade B steel in the "as-rolled" condition used in this study. Thus, all except the early electrogas weld would appear to be acceptable for welding "as-rolled" plate, based on weld centre-line NDT behaviour. Only the E7018 weld MR12, the gas-metal-arc weld MR8, and the later electrogas welds MR13-MR15, indicate the use of consumables and procedures which permit equalling or surpassing, at the weld centre-line location, the NDT temperature of -50°F for the normalized 40.8 Grade B steel used in this study.

(11) Charpy testing of the early electrogas welds indicated that the notch ductility of the coarse grain region of the heat-affected zone is not greatly below that of the as-rolled plate but is much lower than that of normalized plate or of the grain-refined portion of this zone. This

coarse grain region is also indicated to be inferior in notch ductility to the fused portion of electrogas welds in 40.8 Grade B steel, at least at a centre-line location, when welds are made with improved gas shielding and electrode as in the more recent tests. In view of the high energy input levels, and relatively slow travel speeds, impairment due to grain coarsening would be expected to be greatest with processes such as electrogas and electroslag welding.

(12) Limited bulge testing showed that mechanical defects such as a mark made by a metal stamp on the plate surface, or small welding defects such as a surface pinhole porosity, can initiate early failure in weldments which would otherwise withstand considerable deformation at -25°F. This supports a conclusion that bulge performance would also be affected adversely by surface irregularities on the weld reinforcement beads. Thus, automatically-made welds having smoother weld surfaces may perform better than manually-made welds even though notch-ductility tests, which use machined bars, hence excluding surface irregularities, indicate better notch ductility for the manually-made weld.

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1. Letter W. P. Campbell to R. M. Lamarche, June 25, 1969.

2. ASTM Designation E208-69 "Standard Method for Conducting Drop-Weight-Test to Determine Nil-Ductility Transition Temperature of Ferritic Steels".

3. CSA Standard W48.1-1969 - Mild Steel Covered Arc-Welding Electrodes.

4. CSA Standard W48.4-1970 - Solid Mild Steel Electrodes for Gas Metal-Arc Welding.

5. CSA Standard W48.5-1970 - Mild Steel Electrodes for Flux-Cored Arc Welding.

6. CSA Standard W48.6-1970 - Bare Mild Steel Electrodes and Fluxes for Submerged Arc Welding.

7. Standard Evaluation Procedures for Explosion Bulge Testing (Weldments) Including Preproduction Tests of HY-80 Steel, Navships 250-637-6 - Bureau of Ships, Navy Department, Washington, D. C.

8. AWS Structural Welding Code - D1.1-72.

9. Snowy Mountains Hydro-Electric Authority, "Economy of Submerged Arc Welding of AS151 Steel Plate", Australian Welding Journal, Vol. 15, No. 9, 1971 (November/December), p 7.

TABLE 2

NDT Temperatures and Charpy V-Notch Impact Values at Various Temperatures for Welds Notched at Centre-Line

No.	Welding Process/Procedure	NDT Temp. °F	Average Charpy Value (ft-lb) at NDT Temp.	-40°F	-25°F	-20°F	0°F	Temp. for 15 ft-lb °F
MR2	Metal-arc, E7016, flat position	-40	74	74	72	71	73	<-80
MR4	Metal-arc, E7016, vertical-up position	-30	40	28	46	52	54	-56
MR6	Gas metal-arc, E60S3, Argon-oxygen, flat position	-20	61	33	54	61	84	<-100
MR8	Gas metal-arc, E70T-1, CO_2, flat position	-50	14	17	22	24	33	-49
MR9	Submerged arc, F72-EH14, flux/wire, flat position	-	12*	9	17	22	23	-27
MR10	Submerged arc, F72-EH14, flux/wire, flat position	-30						
MR12	Metal-arc, E7018, flat position	-50	37	42	65	73	86	<-60
	Early Electrogas***, E60S3, vertical	-8	20	9	17	19	21	-30
MR13	Electrogas, Avacor, vertical	<-124	16**	36	40	41	55	-128
MR14	" " "	-102						
MR15	" " "	-123						
MR16	Electroslag, Linde MC-70 electrode, Linde 124 flux, vertical	-40	9	9	12	13	14	2

*From Charpy transition curve for MR9 and NDT for MR10 (Figure 5).
**Absorbed energy value at -124°F.
***With A675 electrode (E60-S3) and only one gas port. Later welds with the Avacor electrode made with improved shielding from two gas ports.

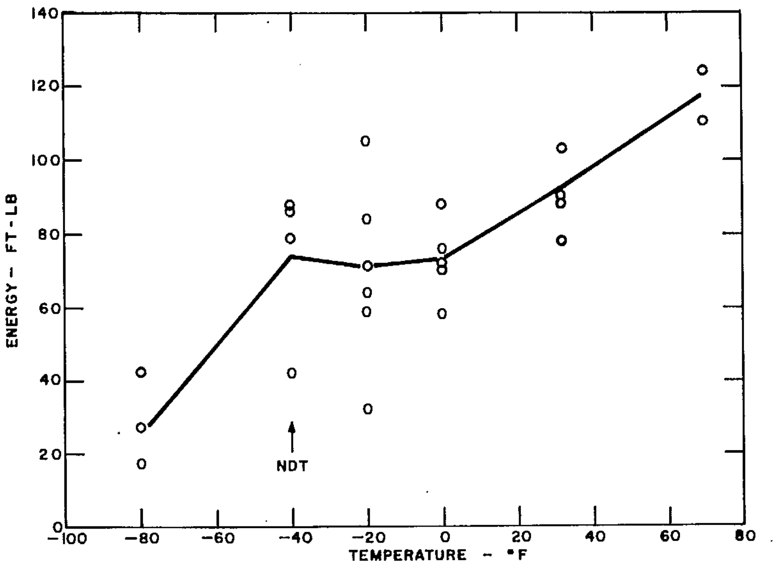


Figure 1. Weld MR2 - metal-arc process, E7016 electrode, flat position.

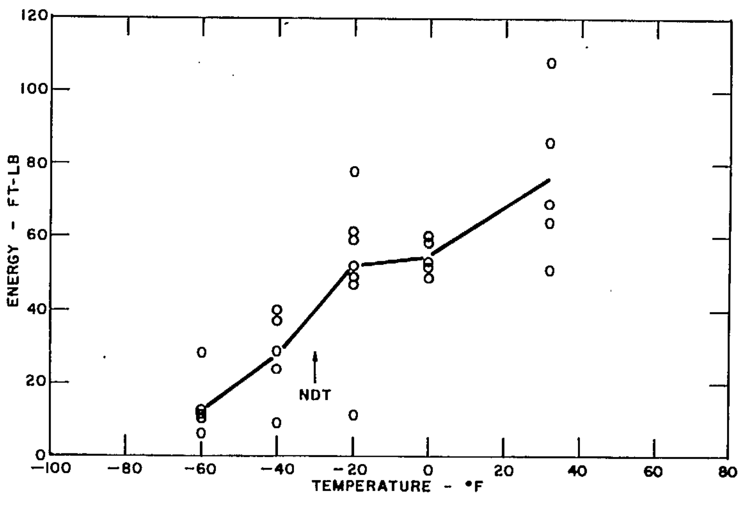


Figure 2. Weld MR4 - metal-arc process, E7016 electrode, vertical-up position.

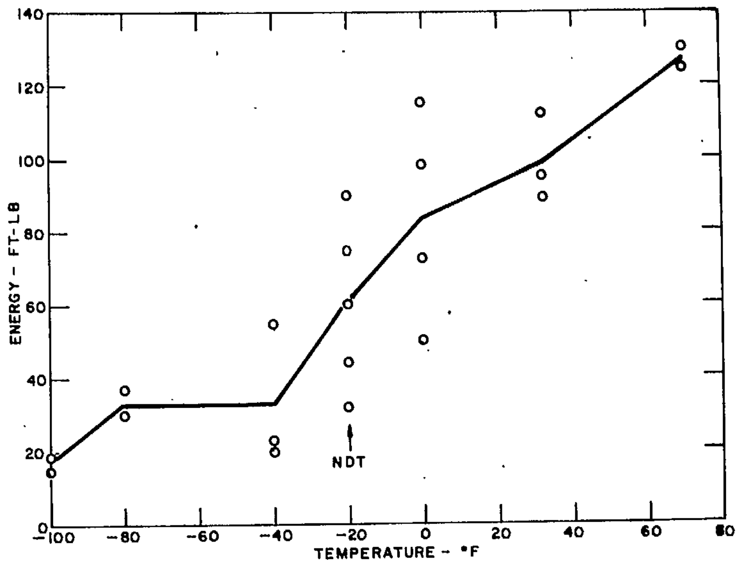


Figure 3. Weld MR6 - gas metal-arc process, E60S-3 electrode, flat position.

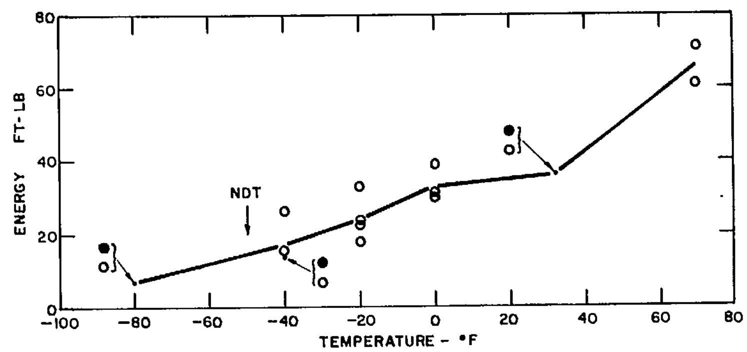


Figure 4. Weld MR8 - gas metal-arc process, E70T-1 electrode, flat position.

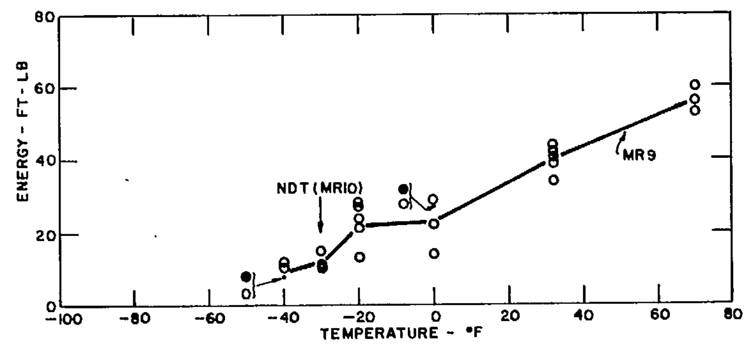


Figure 5. Welds MR9 and MR10 - submerged arc process, F72-EH14 flux/electrode, flat position.

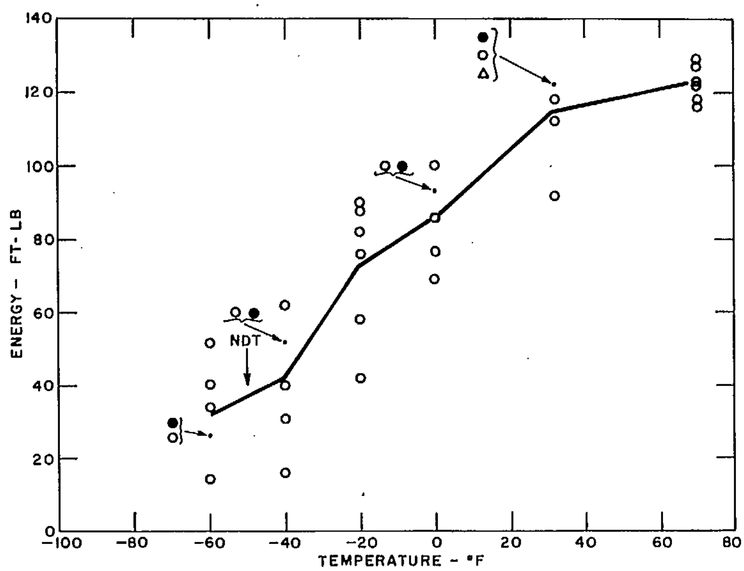


Figure 6. Weld MR12 - metal-arc process, E7018 electrode, flat position.

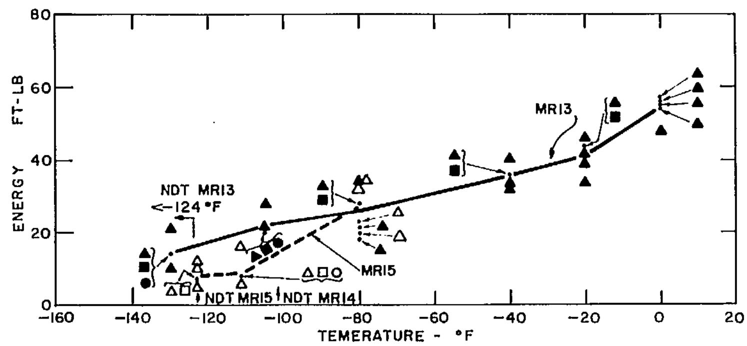


Figure 7. Welds MR13, MR14 and MR15 - Airco electrogas process, Avacor electrode.

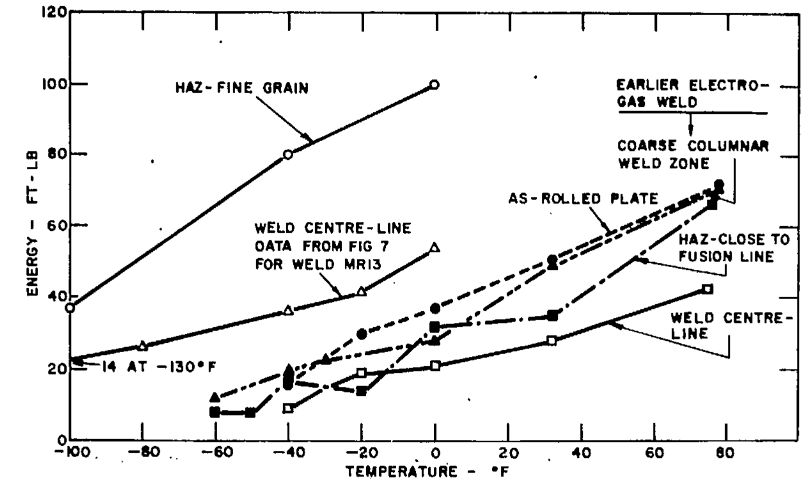


Figure 8. Comparison of Charpy V-notch impact data for earlier electrogas weld, including heat-affected zone, with later weld MR13 and with as-rolled 40.8 Grade B plate.

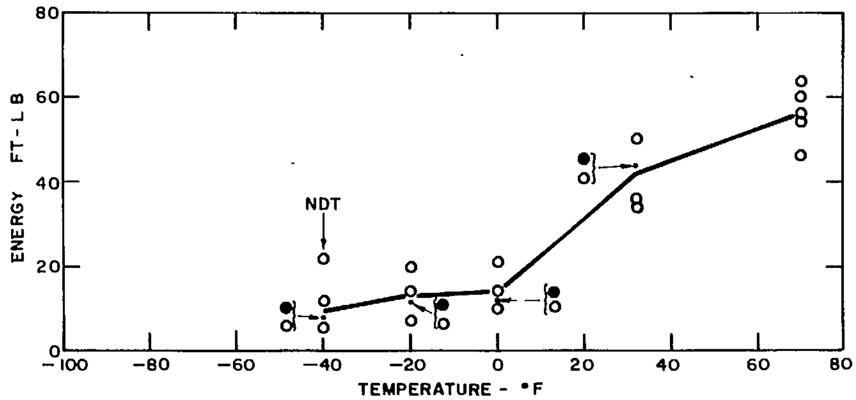


Figure 9. Weld MR16 - Linde electroslag, Linde MC-70 electrode and 124 flux.

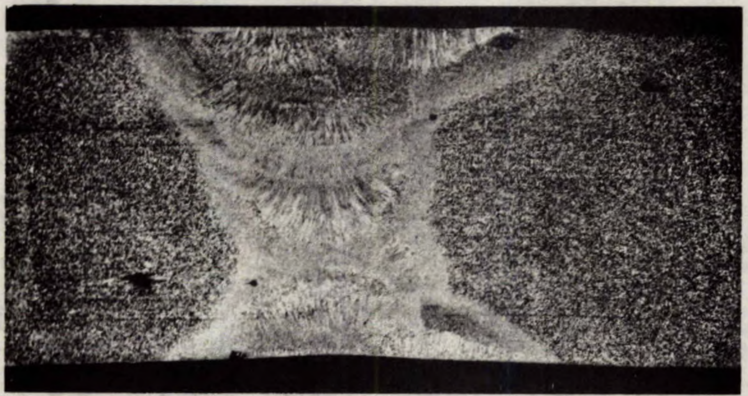


Figure 10. From weld specimen MR2. Metal-arc process, E7016 electrode, flat position.

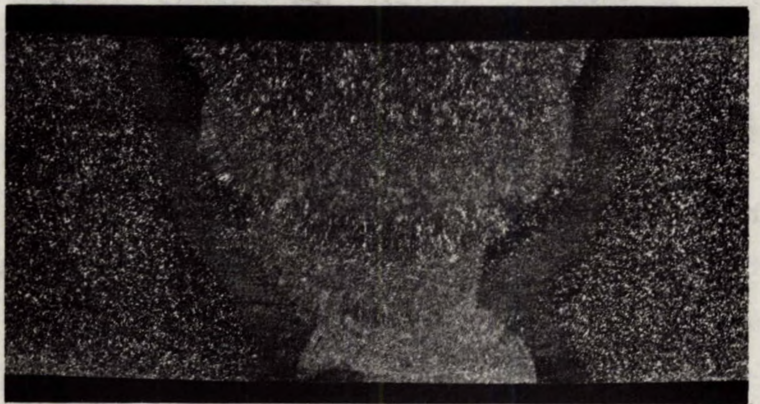


Figure 11. From weld specimen MR4. Metal-arc process, E7016 electrode, vertical-up position.

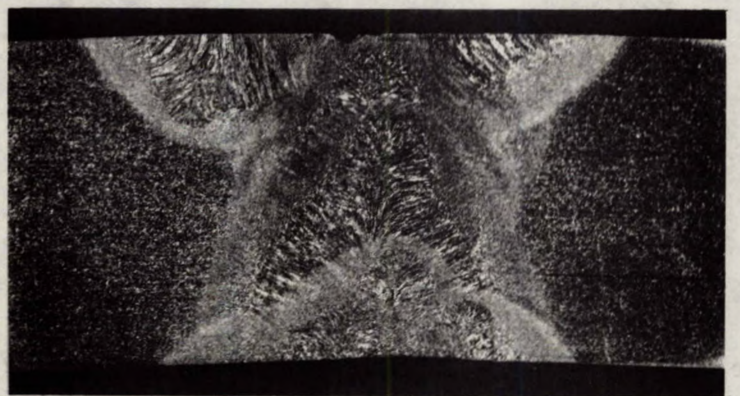


Figure 12. From weld specimen MR6. Gas metal-arc process, E60S-3 electrode, argon-oxygen shielding, flat position.

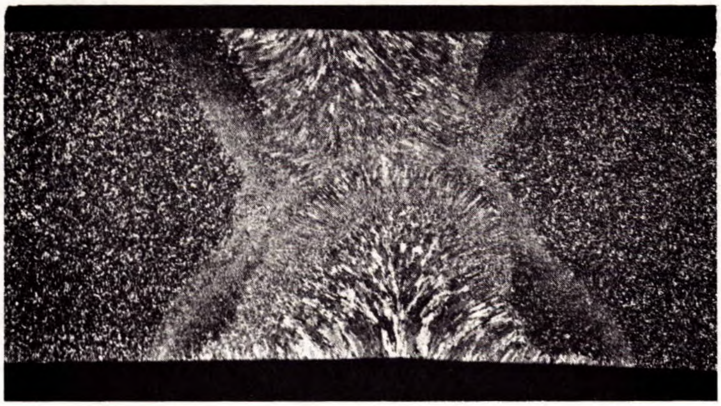


Figure 13. From weld specimen MR8. Gas metal-arc process, E70T-1 electrode, CO_2 shielding, flat position.

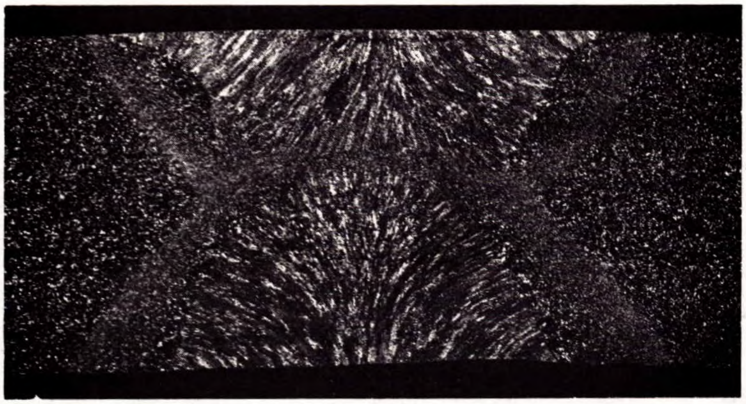


Figure 14. From weld specimen MR10. Submerged arc process, F72 electrode, EH14 flux, flat position.

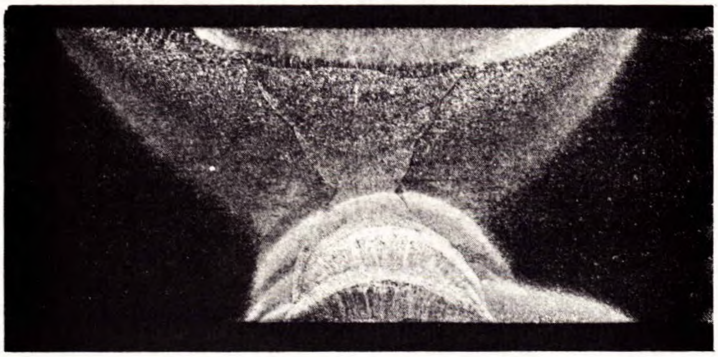


Figure 15. From weld specimen MR12. Metal-arc process, E7018 electrode, flat position.

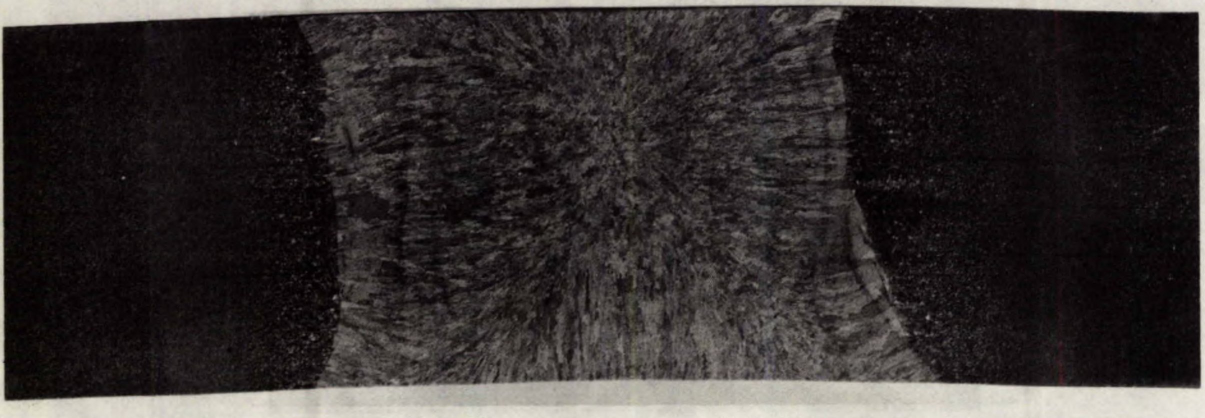


Figure 16. From weld specimen MR13. Electrogas process, Avacor electrode, argon-CO_2 shielding, vertical-up position.

Figure 17. From weld specimen MR16. Electroslag process, Linde MC-70 electrode, Linde 124 flux, vertical-up position.

Figure 18. Failure of submerged arc weld in "as-rolled" steel after one explosive shot.

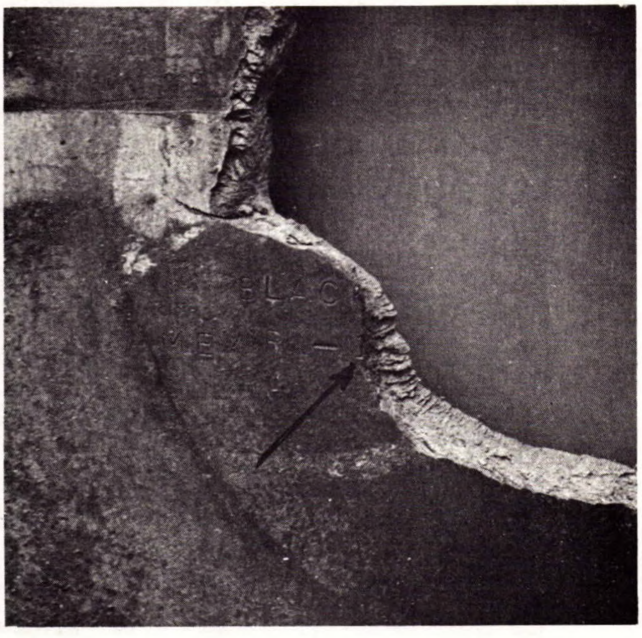


Figure 19. Close-up view of fracture in specimen shown in Figure 18. Arrow points to initiation site.

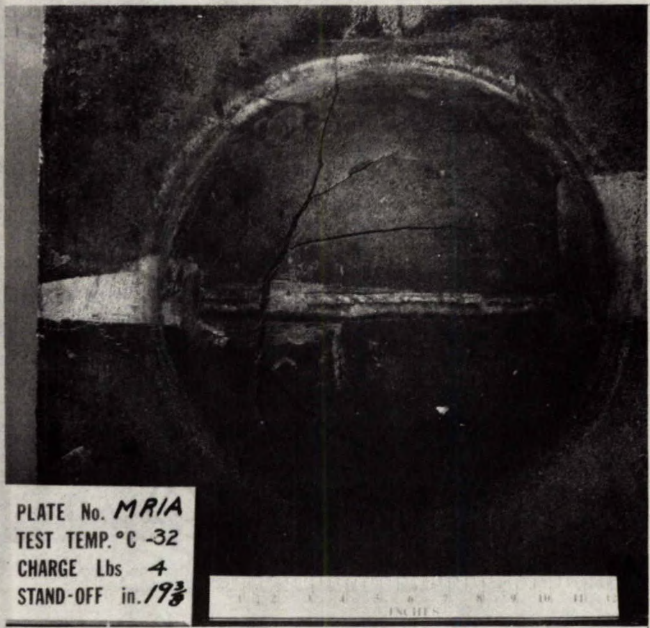


Figure 20. Failure of MR1A weld in normalized plate made manually in the flat position with an Airco E7016 special electrode. No cracking after 3 shots giving total thickness reduction of about 7% and a bulge height of 2 9/16 in. The cracking shown occurred on the fourth shot.

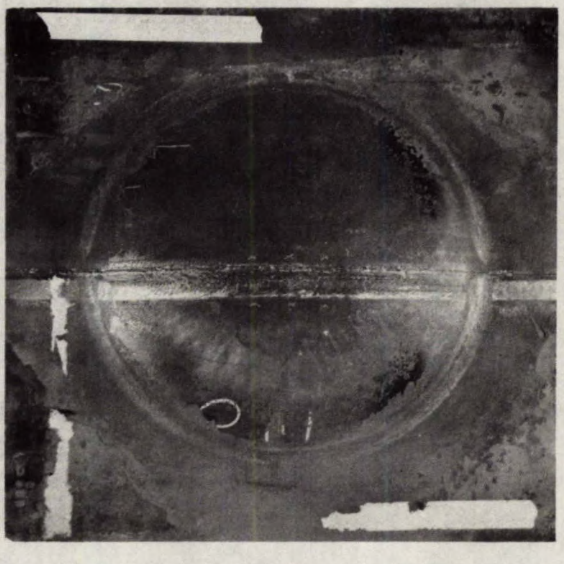


Figure 21. No cracking in an early electrogas weld made with A675 electrode in as-rolled plate after being bulge tested at -36°F. Five shots were employed to produce a bulge depth of 2 7/16 in. and a thickness reduction of about 8%.

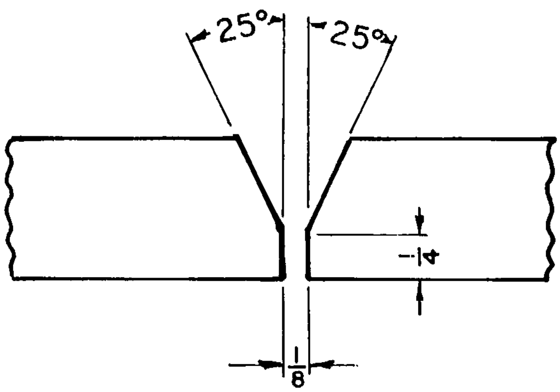
APPENDIX A

WELDING PROCEDURE DATA

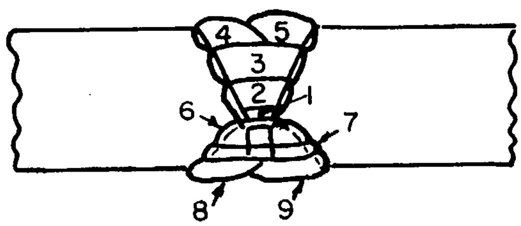
Specimens MR1 and MR2

Welding Process	:	Shielded Metal-arc
Welding Position	:	Flat
Electrode	:	Airco Special to E7016 classification of AWS A5.1-64T.
Current	:	DC - reverse polarity
Plate	:	MR1 in normalized, MR2 in as-rolled.

Joint Preparation



Sequence of Passes



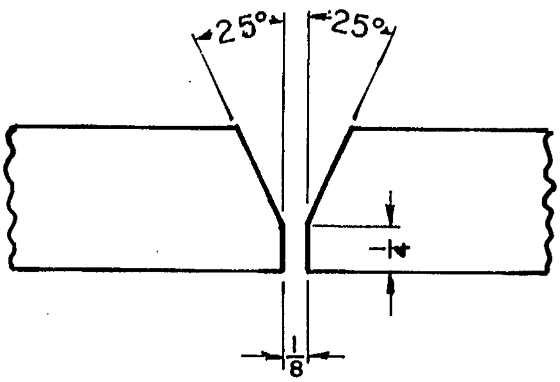
Arc-Air back gouge to sound metal before pass No. 6

Pass No.	:	1, 2, 6	3, 4, 5, 7, 8, 9.
Electrode Diam. in.	:	5/32	3/16
Amperage	:	150-160	190-210
Voltage	:	24-26	25-27
Speed of Travel (ipm)	:	5-7	5-6
Welded by	:	MR1 by A. Grimard, MR2 by J. Daneau, Marine Industries Limited.	
Date welded	:	November 10-12, 1969.	

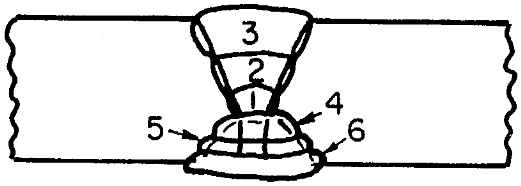
Specimens MR3 and MR4

Welding Process	:	Shielded metal-arc.
Welding Position	:	Vertical up.
Electrode	:	AWS A5.1-64T.
Current	:	DC - reverse polarity.
Plate	:	MR3 in normalized, MR4 in as-rolled.

Joint Preparation



Sequence of Passes



Arc-Air back gouge to sound metal before pass No. 4

Pass No.		1, 4	3	2, 5, 6
Electrode Diam. (in.)	:	1/8	5/32	5/32
Amperage	:	125-130	-	135-145
Voltage	:	23-25	-	25-27
Speed of Travel (ipm)		2-3	1.5-2.5	2-3

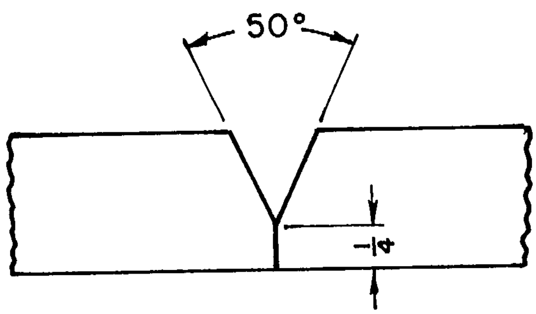
Welded by: J. Daneau, Marine Industries Limited.

Date welded: November 17-18, 1969.

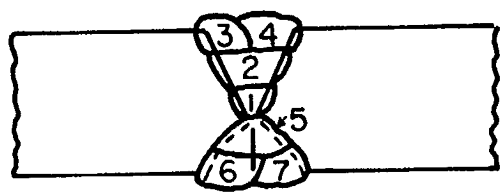
Specimens MR5 and MR6

Welding Process	:	Gas metal-arc.
Welding Position	:	Flat
Electrode	:	Reid Avery Raco - HT to E60S-3 classification of AWS A5.18-65T.
Shielding Gas	:	98% argon-2% oxygen at 30 to 40 c.f.h.
Current	:	DC (constant potential source)
Plate	:	MR5 in normalized, MR6 in as-rolled.

Joint Preparation



Sequence of Passes



Arc-Air back gouge to sound metal before pass No. 5

Pass No.		1, 2	3, 4, 5, 6, 7
Electrode Diam. (in.)	:	1/16	1/16
Amperage	:	320-340	320-340
Voltage	:	28-30	28-30
Speed of Travel (ipm)	:	13-15	12-14

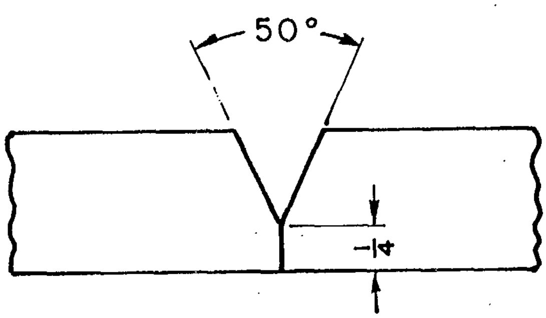
Welded by: A. Grimard, Marine Industries Limited.

Date welded: November 20 and 24, 1969.

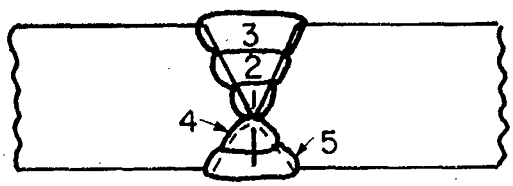
Specimens MR7 and MR8

Welding Process	:	Gas metal-arc
Welding Position	:	Flat
Electrode	:	Alloy Rods Dual Shield 78 to classification E70T-1 of AWS A5.18-65T.
Shielding Gas	:	Carbon-dioxide at 35 to 40 cfh.
Current	:	DC - (constant potential source)
Plate	:	MR7 in normalized, MR8 in as-rolled.

Joint Preparation



Sequence of Passes



Arc-Air back gouge to sound metal before pass No. 4

Pass No.:		1, 2, 3, 4, 5.
Electrode Diam. (in.)	:	3/32
Amperage	:	390-410
Voltage	:	29-31
Speed of Travel (ipm)	:	13-15

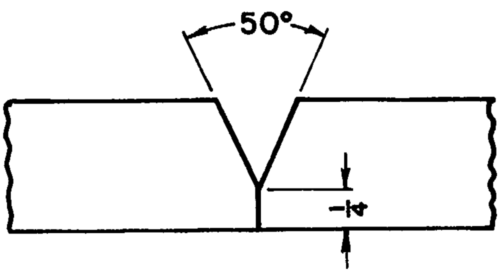
Welded by: A. Grimard, Marine Industries Limited.

Date Welded: November 18, 1969.

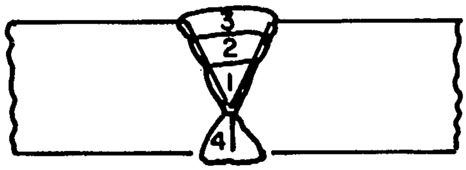
Specimens MR9, MR9A*, MR10, and MR10A*

Welding Process	:	Submerged arc
Welding Position	:	Flat
Electrode	:	Linde AXW-36 to classification EH14 of AWS A5.17-65T.
Flux	:	Linde 585 to classification F72 of AWS A5.17-65T.
Current	:	AC
Plate	:	MR9 and MR9A in normalized, MR10 and MR10A in as-rolled.

Joint Preparation



Sequence of Passes



Arc-Air back gouge to sound metal before pass No. 4

Pass No.		1	2	3	4
Electrode Diam. (in.)	:	3/16	3/16	3/16	3/16
Amperage		700-720	700-720	770-790	780-800
Voltage	:	32-35	32-35	34-35	34-36
Speed of Travel (ipm)	:	22-24	19-21	15-16	12-14

Welded by: All by Marine Industries Limited; MR9 and MR10 by A. Grimard.

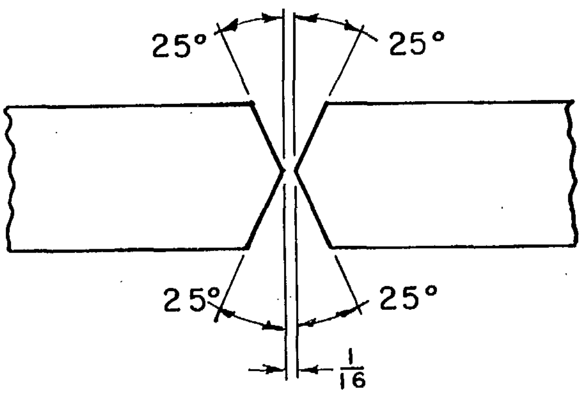
Date Welded: MR9 and MR10 on November 19 and 20, 1969 and MR9A and MR10A during February to April 1970.

*These were repeat specimens produced by Marine Industries and it was understood that the same consumables and welding procedures as for MR9 and MR10 were employed.

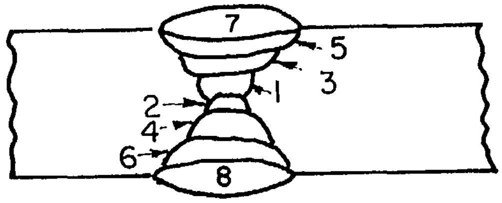
Specimens MR11 and MR12

Welding Process	:	Metal-arc
Welding Position	:	Flat
Electrode	:	Canadian Liquid Air to E7018 classification of CSA W48.1-1969.
Current	:	DC - reverse polarity
Plate	:	MR11 in normalized, MR12 in as-rolled.

Joint Preparation



Sequence of Passes



Grind to sound metal before pass No. 2.

Pass No.		1, 2, 3, 4	5, 6, 7, 8
Electrode Diam. (in.)	:	5/32	3/16
Amperage	:	160-180	250-270
Voltage	:	22-24	22-24
Speed of Travel (ipm)	:	5-7	5-7

Welded by: L. O. Joy, Physical Metallurgy Division.

Date welded: April, 1971.

Specimens MR13, MR14 and MR15

Welding Process	:	Airco Electrogas (gas shielding from two ports).
Welding Position	:	Vertical.
Electrode	:	5/64 in. Airco Avacor
Plate	:	Normalized
Joint Preparation	:	Square butt, 1/2 in. gap.
Current	:	DC - reverse polarity, 400-420 amperes for MR13, 500-520 amperes for MR14 and 475-530 amperes for MR15.
Voltage	:	31.5 volts.
Electrode feed speed	:	350 ipm
Speed of Travel	:	2 1/4-2 1/2 ipm for MR13, 3 1/4 ipm for MR14 and MR15
Shielding Gas	:	Argon 110 cfh, carbon dioxide 25 cfh

Welded by: L. O. Joy and G. Sylvestre, Physical Metallurgy Division.

Date Welded: February and May 1972.

Supplementary note: An all weld metal tensile specimen machined centrally from weld MR13, parallel to its longitudinal axis, gave the following properties: UTS - 98.1 kpsi, 0.2% Y.S. - 75.3 kpsi, % Elongation in 2 in. - 26.5%, and Reduction of Area - 66.5%.

MR16-MR17 Inclusive

Welding Process	:	Electroslag using Linde ES-5 Plate Crawler, 600 ampere constant potential power supply, and a water pump/cooler.
Welding Position	:	Vertical
Electrode	:	Linde MC-70 (flux-cored).
Flux	:	Linde 124.
Plate	:	Normalized
Joint Preparation	:	Square butt, 3/4 in. gap.
Current	:	420-440 amperes.
Voltage	:	34-35 volts.
Flux Depth	:	1½-2 in.
Electrode Extension	:	1½-2 in.
Travel Speed	:	2-2.2 ipm.

Welded by: Union Carbide Canada Limited under direction of J. D. Makarchuk.

Date Welded: Late in 1972.

"Early" Electrogas Weld

Welding Process	:	Airco Electrogas - gas shielding from one port only.
Welding Position	:	Vertical
Electrode	:	1/16 in. Airco A675 to E60S-3 classification of AWS A5.18-65T.
Plate	:	As-rolled 40.8 Grade B steel - from same heat as all other specimens in current project.
Joint Preparation	:	Square butt, 1/2 in. gap.
Current	:	DC reverse polarity, 340-350 amperes.
Voltage	:	35-36 volts.
Electrode feed speed	:	340-350 ipm.
Speed of Travel	:	2.1 ipm.
Shielding Gas	:	Argon 30 cfh, carbon dioxide 6.4 cfh.

Welded by: L. O. Joy and G. Sylvestre, Physical Metallurgy Division.

Date Welded: July 1965.