WELDING RESEARCH

SUPPLEMENT TO THE WELDING JOURNAL, FEBRUARY, 1980
Sponsored by the American Welding Society and the Welding Research Council

Weldability of a Low-Carbon Mo-Nb X-70 Pipeline Steel

Better SMAW and GMAW techniques and consumables offering higher toughness at lower temperatures than those presently used for pipeline construction in North America appear to be needed to meet weld zone requirements at −20°C (−4°F)

BY A. J. BRYHAN AND W. TROYER

ABSTRACT. Low-carbon Mo-Nb steel pipe possesses an advantageous combination of high strength and toughness coupled with good weldability. The low (0.10% or less) carbon content combined with fine grain structure provides the combination of high strength and good toughness especially suited to Arctic pipeline applications. The low carbon content of these steels also contributes to good weldability.

Field weldability of a Mo-Nb X-70 pipeline steel was demonstrated comparing shielded metal arc (SMA) and gas metal arc (GMA) welding techniques using four electrode/process combinations including cellulosic electrodes as well as low-hydrogen electrodes in the vertical-up and vertical-down positions. Weld quality was assessed using guided bend, tensile, drop-weight, nick-break, Charpy V-notch, and crack opening displacement (COD) tests. Performance of the X-70 pipe was also examined using tensile and hardness tests and chemical and metallographic analysis. Fracture toughness was measured at −4°C (+25°F), −23°C (−10°F) and −51°C (−60°F). In addition, the Mo-Nb X-70 pipeline steel was subjected to im-plant testing to establish its resistance to hydrogen assisted cracking.

Tests were evaluated comparing the results to the Foothills Pipe Lines (Yukon) Ltd. and the American Petroleum Institute (API) 1104 specifications. All weldments were found to be suitable for service at −4°C (+25°F) meeting the Charpy toughness criteria of 51 J (38 ft-lb). However, the various electrode/process combinations gave deposits which showed mixed performance at −23°C (−10°F) and exhibited too low toughness at −51°C (−60°F). While the Mo-Nb X-70 pipe was satisfactory, it would appear that better techniques/consumables, offering higher toughness at these lower temperatures, are needed to meet the weld zone requirements at −20°C (−4°F).

Paper presented at the AWS 60th Annual Meeting held in Detroit, Michigan, during April 2-6, 1979.

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Introduction

New higher strength pipe steels have been developed to handle transportation of petroleum products from Arctic regions. The current generation of high strength steel pipe for gas transmission lines is designated as API X-70 grade. A particular variety of steel, the low carbon Mo-Nb type used in X-70 pipe, offers an advantageous combination of high strength and toughness plus good weldability. Steels of this type have been available since 1970, and several pipelines in North America and the Soviet Union are currently in operation using these steels. Because the Mo-Nb steels are relatively new, only a little weldability information is available in the literature. The purpose of this paper is to review recent work conducted on a few of the available welding processes and consumables.

The steel used for the study was manufactured by USINOR and made into pipe by Vallourec, both of France. These companies currently supply X-70 skelp and pipe commercially. The nominal maximum composition is 0.10% C, 1.5% Mn, 0.22% Mo, and 0.067% Nb. This is a pearlite-reduced

grade which was finish rolled at a low temperature. The low temperature rolling produced some deformed ferrite. The high density of mobile dislocations in this ferrite promotes a continuous stress-strain behavior with increased work hardening which more than offsets the loss of strength commonly associated with the Bauschinger effect.[1]

Four welding consumables and/or process variations of potential interest were selected for this study. These included cellulosic electrodes, vertical-up and vertical-down low-hydrogen electrodes for shielded metal arc welding (SMAW), plus a solid wire electrode for semiautomatic gas metal arc welding (GMAW). The consumables were selected to be compatible with the usual or desired methods currently employed for pipeline construction. The welding procedures were to be typical of those practiced in North America.

The use of cellulosic electrodes combines relatively high production rates with welder acceptance and results in high quality welds if certain precautions are used to reduce hydrogen assisted cracking (HAC) in the root area of a pipe weld. The root passes of a weld are especially susceptible to HAC which is due to the combination of small weld bead size, high joint constraint, and the low pipe temperature which reduces the rate of hydrogen diffusion. To reduce the susceptibility to HAC, the three abovementioned low-hydrogen electrodes/techniques were incorporated into this study.

The gas metal arc welding (GMAW) process is an inherently low-hydrogen process as virtually no hydrogen is introduced into the weld by the consumables. Although the GMAW process potentially offers advantages, it has not gained wide acceptance for field welding of pipe. Hydrogen assisted cracking may also be controlled by using low-hydrogen shielded metal arc welding (SMAW) electrodes. The flux coating on these electrodes is not cellulosic; thus hydrogen is not generated by dissociation of the flux in the welding arc.

Two types of low-hydrogen electrodes are available—a type that is used in a vertical-up direction, and a type that is used in a vertical-down direction. The vertical-up electrode has been available for many years. It has been used most frequently for welding parts that are of a critical nature such as valves and fittings. Some of the reasons why this electrode is not used for routine welding are that these electrodes are more expensive, the deposition rate is not as high and they are not as convenient to use as cellulosic electrodes.

Because of the difficulties with the vertical-up type electrodes, vertical-down low-hydrogen electrodes are being developed. These electrodes seek to combine the ease of welding and productivity of the cellulosic electrodes with a low diffusible hydrogen content. The intent is to design electrodes which may be used with essentially the same technique as a cellulosic type electrode, thus requiring less welder training.

The proposed Alaskan Highway Pipeline Project, which will transport natural gas from the North Slope in Alaska to markets in the northwestern and eastern parts of the United States, will be a large consumer of X-70 grade pipe. One section of this project is the Foothills pipeline which crosses the Yukon, British Columbia and Alberta. The pipe for this section will have diameters which vary from 914 mm (36 in.) to 1422 mm (56 in.) and wall thickness ranging from 10 mm (0.40 in.) to 18 mm (0.72 in.). The total length for this section will be 2848 km (1780 miles). The design temperature is to be −4°C (+25°F) for the majority of the line with a minimum service temperature of −20°C (−4°F) for approximately 2% of the total length. This lower design temperature is also likely to be applied for the Alaskan section of the project.

It was decided to use the specifications for the Foothills section to evaluate the success of the welding in this study. In addition to the testing specified by Foothills which is discussed later, a complete characterization of the girth weld and associated heat-affected zones (HAZ) was made using

Table 1—Mechanical Properties and Composition of USINOR X-70 Pipe Steel

0.2% yield stress, MPa (ksi)	Ultimate tensile stress, MPa (ksi)	Elongation, %	Reduction in area, %	Yield tensile ratio
488 (70.8)	644 (93.5)	19.1	33.9	0.76

Foothills Pipe Line (Yukon) Ltd. Specification:
Yield stress: minimum 482 MPa (70 ksi); maximum less than 586 MPa (85 ksi)
Yield to Ultimate Tensile Strength Ratio less than 0.90

Chemical Composition %

C	*Mn*	*Si*	*P*	*S*	*Nb*	*Mo*
0.093	1.53	0.18	0.024	0.004	0.057	0.22

Table 2—Chemical Composition of Welding Electrodes and Resulting Deposits, %

Electrodes[a]	C	Mn	Si	P	S	Ni	Mo	Cu	Cr	V	Ti	Nb
E8010	0.14	0.45	0.15	0.015	0.010	1.50	0.17	—	—	—	—	—
E8018-C1	0.04	1.04	0.31	—	—	2.37	—	—	—	—	—	—
E70S-1B	0.10	1.30	0.22	0.021	0.015	—	0.42					
Kobe LB-86VU	0.07	0.98	0.45	0.012	0.007	1.57	0.50					
Weldments												
1 E8010/8010	0.15	0.52	0.22	0.016	0.009	1.24	0.20	0.021	0.062	0.008	0.015	0.01
2 E70S-1B/8010	0.15	0.44	0.21	0.012	0.011	1.39	0.19	0.018	0.025	0.010	0.020	<.01
3 E70S-1B/8010-C1	0.062	0.92	0.30	0.013	0.013	2.21	0.048	0.019	0.045	0.014	0.010	<.01
4 E70S-1B/LB-86VU	0.051	0.96	0.37	0.014	0.006	1.37	0.46	0.014	0.025	0.007	0.009	0.01

[a]Analysis supplied by manufacturer.

Table 3—Welding Parameters and Consumables

Consumables:

E8010	4 mm (5/32 in.) root and hot passes 5 mm (3/16 in.) fill passes
E8018-C1	4 mm (5/32 in.) fill passes
E70S-1B with CO_2 shielding gas at 14 1/min (30 cfh)	0.9 mm (0.035 in.) root and hot passes
Kobe LB-86VU	4 mm (5/32 in.) fill passes

Average Welding Parameters:

	Current, A	Voltage, V	Travel speed, mm/s (ipm)	Heat input, MJ/m (kJ/in.)
E8010 Root-hot passes	125	24	6.0 (14.0)	0.5 (12.9)
E8010 Fill passes	180	32	2.8 (6.5)	2.1 (53.9)
E70S-1B Root-hot passes	155	22	2.8 (6.5)	1.2 (31.5)
E8010-C1 Fill passes	140	23	1.0 (2.5)	3.0 (77.3)
Kobe LB86-VU Fill passes	200	27	3.8 (9.0)	1.4 (36.0)

the crack opening displacement (COD) test. Up until this time, fracture toughness tests, such as the COD method, have only been used by pipeline companies for informational purposes.

Experimental Procedures

Materials

The composition and mechanical properties of the pipe steel used for this investigation are presented in Table 1. This pipe material is an X-70 grade, pearlite-reduced Mo-Nb steel. The material was supplied by Vallourec of France from three heats of nominally identical steel and was used in this project without regard to any possible effects of heat-to-heat variations. The pipe was 1219 mm (48 in.) in diameter with a 16 mm (0.661 in.) wall thickness. The three pipe sections used for this study were 1 m (39 in.) long. The ends were bevelled to a 30 deg angle with a root face approximately 1.6 mm (1/16 in.) wide.

This pipe was welded using four consumables—E 8010 cellulosic electrodes, E 70S-1B electrodes with the GMA process using carbon dioxide for shielding gas, E 8018-C1 vertical-up low-hydrogen electrodes, and a developmental vertical-down low-hydrogen electrode manufactured by Kobe Steel and designated LB-86VU. The compositions of the electrodes and resulting weldment deposits are listed in Table 2.

These four consumables were combined to produce weldments typical of those used in actual pipeline construction. Four welds were made:

1. E 8010 used for root, hot, and fill passes.
2. E70S-1B used for the root and hot passes and E 8010 used for fill.
3. E 70S-1B used for the root and hot passes and E 8018-C1 used for fill.
4. E 70S-1B used for the root and hot passes and the Kobe LB-86VU vertical-down low-hydrogen used for the fill passes.

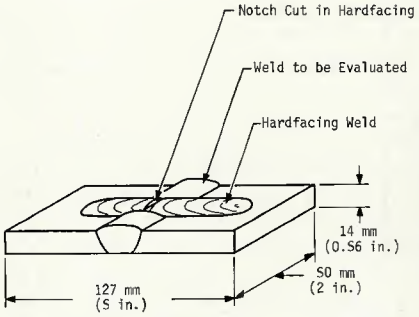


Fig. 1—Dropweight test specimen, ASTM-E208-69

Welding

The shielded metal arc welding (SMAW) was performed by welders supplied by a North American pipeline company. The GMAW root welds were made by a technician from an electrode manufacturing company. Welding conditions and electrode details are described in Table 3. Welds were made without preheating the pipe. This is considerably more severe than a typical field welding procedure, since virtually all commercial field welding of large diameter pipe would be performed on pipe preheated to 100–150°C (212–300°F). Welding without preheat was done to determine if hydrogen assisted cracking would occur. The ambient temperature was in the range of 15–21°C (60–70°F).

The girth weld made using the E 8010 cellulosic electrode for all passes simulates the technique which is most frequently used in the field. This procedure was to be used as a comparison base for evaluating the other electrode procedures. It was thought that the welders should have been thoroughly

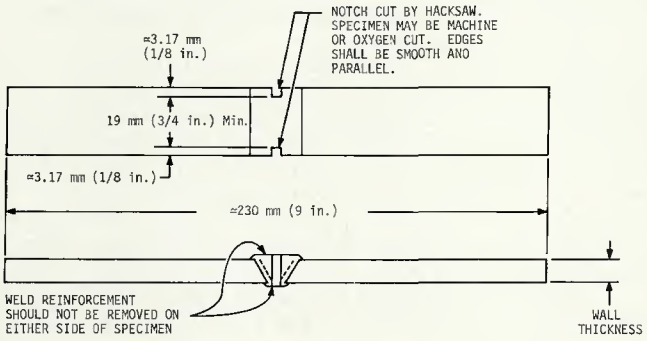
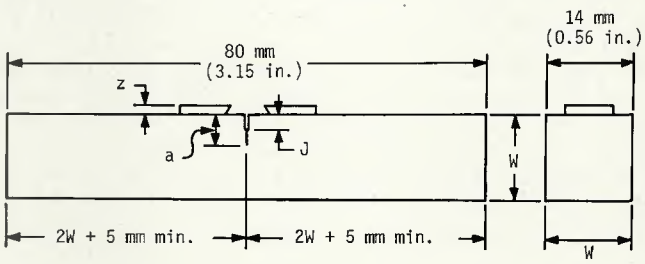


Fig. 2—Nick-break test specimen



$$\delta_c = \frac{V_c}{[3(a+z)/(W-a)]+1} = \text{Critical COD value}$$

V_c = Value of clip gauge displacement

a = Crack length, i.e. machined notch length plus fatigue crack length

z = Distance of clip gauge from test piece surface

W = Test piece width

J = Machined notch length = 2 mm (0.079 in.)

Fig. 3—(right)—Crack opening displacement (COD) test specimen and critical COD equation

familiar and have no difficulties with this electrode.

When using the GMAW process for the remaining welds, however, difficulties were encountered in trying to obtain adequate penetration. Limited on-site experimentation indicated that a wider root gap was required for the GMA weld as compared to the SMA weld because arc penetration was less for the GMAW process. An opening of at least 3 mm (⅛ in.) seemed necessary. Keeping a uniform gap was difficult with the experimental set-up and, as a consequence, root penetration proved to be a continuing problem. The GMA welding technique was acceptable in all other respects.

Actual welding performance of the vertical-up E 8018-C1 low-hydrogen electrode was good. No difficulties were encountered. A weaving technique was employed to deposit the filler metal.

For the Kobe LB-86VU vertical-down low-hydrogen electrode, it was necessary to deposit stringer passes with no weaving of the electrode in order to keep the welding arc ahead of the molten flux. This resulted in a number of stringers being used to weld the joint rather than a large flowing puddle as with the vertical-up process. Electrode travel speed varied by about a factor of four between the two processes. The time required to complete the weld was about the same, however, as the Kobe weld required 11 passes and the E 8018-C1 weld required only two (three passes were required for the 10–12 o'clock positions).

Although the pipeline company personnel making the welds had not used the vertical-down type electrodes prior to this trial, they seemed to adjust to the required procedures quickly and experienced what seemed at the time to be only minor difficulties. One such difficulty was the method used to start the welding arc. Usual cellulosic electrode welding practice is to strike the electrode tip in the joint and then quickly draw it back, thus forming the welding arc across the gap. When this technique was used for the Kobe electrodes, severe porosity was encountered. It was found, after the weld was almost complete, that a better technique was to bring the electrode tip near the surface of the joint but without actually touching it. A special tip material on each electrode facilitated arc initiation with a small tip-to-work distance. Large distances caused insufficient shielding action and resulted in porosity.

Table 4—Typical Welding Parameters for the Implant Test

Process: shielded metal arc welding (SMAW)
Voltage: 28–32 V
Current: 150–155 A
Travel speed: 4.7 mm/s (11 ipm)
Average heat input: 0.98 MJ/m (25 kJ/in.)
Preheat: none
Ambient temperature: 23°C (73°F)
Electrode: Lincoln Shield Arc X-70, E-8010-G, 4 mm (3/32 in.) diameter
Implant test schedule:

Relative time, minutes	*Action*
0	Weld deposited
2	Weld surface cooled in water
6	Specimen removed from water
10	Specimen loaded in test fixture, testing commences
1000	Test ends for specimens which did not break

Evaluation of Welds

Following completion of the girth welds, the complete circumference of all welds was radiographed using a procedure that exceeded the requirements of both Canadian Standards Association (CSA) Z184 and API 1104. The radiographs were sent to Climax for inspection and to a qualified nondestructive testing technician for actual interpretation. The pipes were sectioned after the completion of radiographic examination and half of the material sent to Climax and half to an electrode manufacturer for testing. The following tests were performed by the electrode manufacturer:

- Transverse weld metal tensile tests.
- Drop weight tests.
- Transverse root and face bend tests.
- Nick break tests.
- Charpy V-notch test in weld metal.
- Chemical analysis of weld metal.

The following tests were performed by Climax:

- Transverse base metal tensile test.
- Charpy V-notch tests of HAZ, root and fill passes.
- Crack opening displacement (COD) tests of HAZ, root and fill passes.
- Metallographic examination.
- Microhardness determination.
- Base metal implant tests.

All toughness tests were performed at temperatures of −4°C (+25°F), −23°C (−10°F) or −51°C (−60°F). Tests performed at −51°C were for information purposes only and are not required by the Foothills specifications.

Drop Weight Test. The testing and evaluation was performed in accordance with ASTM E 208-69. The test uses a small coupon 50 × 127 mm (2 × 5 in.) by the pipe thickness pictured in Fig. 1. The coupon is tested in three point bending applying a 400 J (300 ft-lb) impact load. On the tension face of the coupon and located over the weld zone of interest, a special weld bead is placed parallel to the long coupon axis and perpendicular to the longitudinal axis of the weld to be tested. This second weld is deposited using a hardfacing type electrode and serves as a crack starter into the zone to be tested. This brittle weld bead is notched transversely, thus assuring the precise location of fracture initiation. Successive tests were made at the three temperatures of interest. After impact loading, if the crack extends the full width of the coupon, the sample fails the test. If the crack is arrested before extending completely across the specimen, the sample passes the test.

The temperature above which failure will not occur is called the nilductility transition (NDT) temperature. It is desired that the NDT temperature be lower than the service temperature. The NDT temperature concept is applicable to ferritic steels and has been correlated to service performance of pressure vessels. A NDT temperature lower than the service temperature of the steel implies a certain degree of notch toughness at the service temperature.

Nick-Break Test. This test is described in API Specification 1104. The specimen (Fig. 2) is approximately 230 mm (9 in.) long, 25 mm (1 in.) wide by the pipe thickness. The weld is centered transverse to the coupon.

A small notch is saw cut into each edge of the coupon 3 mm (⅛ in.) deep. This notch locates the crack initiation point. The specimen is then broken by either pulling in a tensile machine, by supporting the ends and striking the center or by supporting one end and striking the other end with a hammer. For this investigation, the specimens were broken by pulling in a tensile test machine.

The requirement of the test is that the exposed surfaces of each specimen

Table 5—Results of Radiographic Analysis of Pipe Welds

Identification	Relative position on circumference, Zero at 12:00	Indications	Conformance
	0-6	Incomplete penetration and porosity	No
	12-18	Incomplete penetration and porosity	No
	18-24	Incomplete penetration and fusion	No
Weld 1	30-36	—	Yes
8010/8010	36-42	—	Yes
	42-48	—	Yes
	48-54	—	Yes
	60-66	Porosity	No
	72-78	—	Yes
	78-84	Porosity	No
	96-102	Porosity and slag	No
	108-114	Slag and porosity	No
Weld 2	114-120	Slag and porosity	No
E70S-1B/8010	126-132	—	Yes
	132-138	Incomplete fusion	No
	138-144	Incomplete fusion	No
	6-12		Yes
	12-18		Yes
	18-24		Yes
Weld 3	36-42		Yes
E70S-1B/8018-C1	48-54		Yes
	54-60		Yes
	66-72		Yes
	72-78	—	Yes
	78-84	—	Yes
	84-96	Incomplete fusion	No
	102-108	—	Yes
Weld 4	108-114	—	Yes
E70S-1B/LB-86VU	120-126	Incomplete penetration	No
	132-138	—	Yes
	138-144	—	Yes

Table 6—Test Results for Drop Weight, Bend and Nick-Break Tests—Testing and Evaluation According to API 1104

Weld no.	Consumables	Drop weight test 406 J (300 ft-lb)			Bend test[a]				Nick break[b]	
					Face		Root			
		−4°C (+25°F)	−23°C (−10°F)	−51°C (−60°F)	1	2	1	2	1	2
1	8010/8010	Pass	Pass	Pass	Pass	Fail	Pass	Pass	Pass	Pass
2	E70S-1B/8010	Pass	Pass	Fail	Fail	Pass	Pass	Pass	Pass	Pass
3	E70S-1B/ 8018-C1	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
4	E70S-1B/ Kobe LB-86VU	Pass	Pass	Fail	Pass	Pass	Pass	Fail	Fail	Pass

[a]Two specimens tested for both root and face bend tests.
[b] Two specimens tested for nick-break tests.

shall show complete penetration and fusion. The greatest dimension of any gas pocket shall not exceed 1.6 mm (1/16 in.) and the combined areas of all gas pockets shall not exceed 2% of the exposed surface area. Slag inclusions shall not be more than 0.8 mm (1/32 in.) in depth nor 3.2 mm (1/8 in.) or 1/2 the nominal wall thickness, whichever is smaller, in length. There shall be at least 12.7 mm (1/2 in.) of sound weld metal between adjacent slag inclusions.

Crack Opening Displacement (COD) Test. The specification for this test is presented in the literature,[2] and the specimen configuration is shown in Fig. 3. The object of this fracture toughness test is to determine the value of the critical crack opening displacement at the tip of a defect at the onset of crack extension. The precracked specimen, in which a fatigue induced sharp crack has been developed from an electrical discharge machined (EDM) notch, is subjected to a three-point slow bending load. A graphical plot is made of applied force vs. clip gauge displacement measured between knife edges adhesive bonded to the specimen. The measured clip gauge displacement at fracture or the onset of crack extension is related to

Table 7—Tensile Properties of Welds—Transverse Weld Metal Test

Weld number	Consumables	Ultimate[a] tensile stress, MPa (ksi)
1	8010/8010	596 (86.4)
2	E70S-1B/8010	591 (85.7)
3	E70S-1B/8018-C1	615 (89.2)
4	E70S-1B/Kobe, LB-86VU	552 (80.1)

[a]All samples failed in the base metal. No yield stress or elongation were reported.

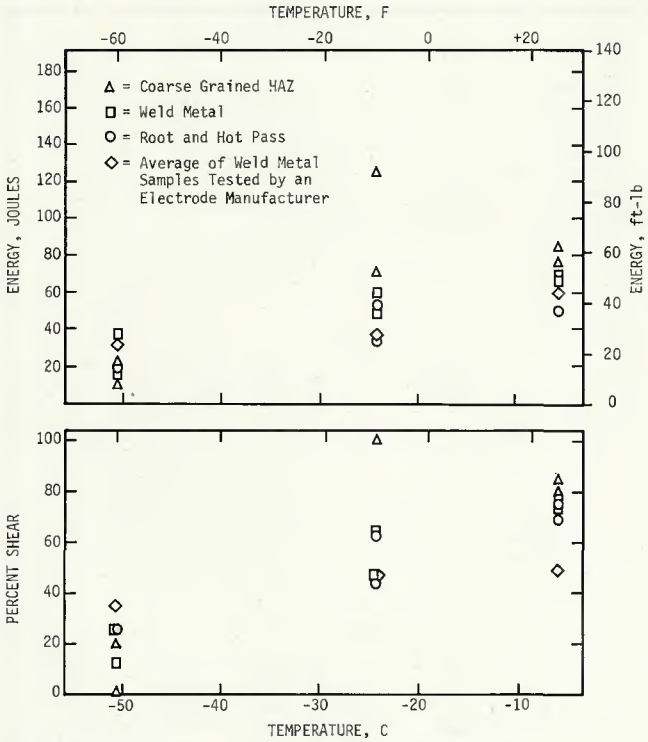


Fig. 4—Results of Charpy V-notch tests performed by Climax on fill and root passes and in the HAZ, weld 1, E8010/E8010

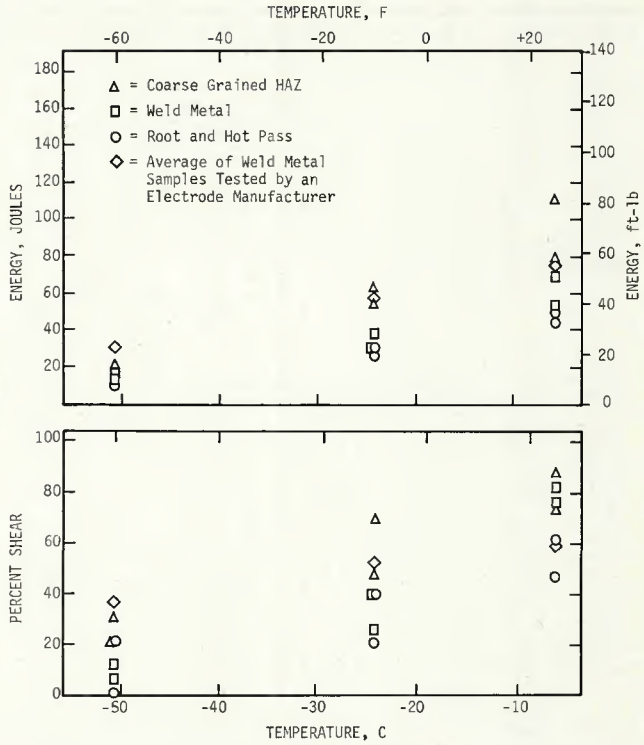


Fig. 5—Results of Charpy V-notch tests performed by Climax on fill and root passes and in the HAZ, weld 2, E70S-1B/E8010

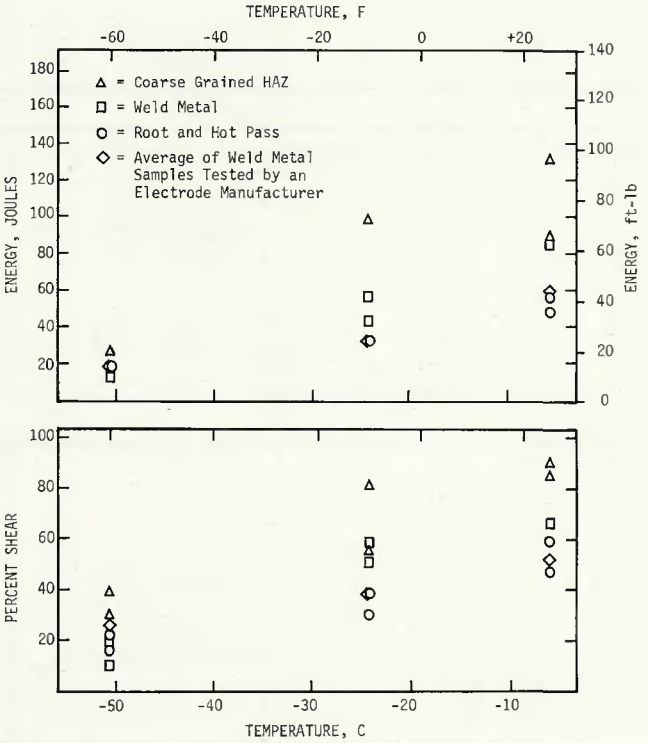


Fig. 6—Results of Charpy V-notch tests performed by Climax on fill and root passes and in the HAZ, weld 3, E70S-1B/E8018-C1

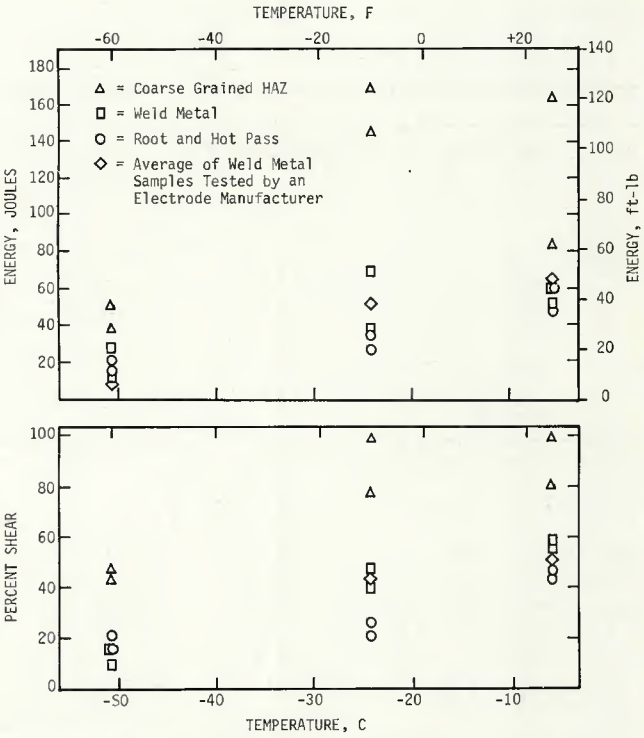


Fig. 7—Results of Charpy V-notch tests performed by Climax on fill and root passes and in the HAZ, weld 4, E70S-1B/Kobe LB-86VU

the crack tip opening displacement (COD) at the test temperature by using a published theoretical equation, which is also included in Fig. 3. The COD value is obtained from an extension of linear elastic fracture mechanics and applies to materials whose ductility does not permit plane strain (K_{Ic}) testing.

For this investigation, specimens were initially notched in the area of interest using an EDM. The depth of this notch was 2 mm (0.079 in.). By fatigue precracking each specimen, this notch was extended an additional 1 to 2 mm (0.04 to 0.08 in.). The precracking load minima and maxima were 66 N (15 lbf) and 8385 N (1885 lbf) for heat-affected zone (HAZ) areas and 71 N (16 lbf) and 8830 N (1985 lbf) for the weld areas. The total

Table 8—Results of Charpy V-Notch (CVN) Tests Performed by an Electrode Manufacturer, Five Samples Tested, At Each Temperature, J (ft-lb)

Weld Number	−4°C (+25°F)			−23°C (−10°F)			−51°C (−60°F)		
	Low	High	Average	Low	High	Average	Low	High	Average
1	50 (37)	74 (55)	61 (45)	28 (21)	60 (44)	49 (36)	20 (15)	41 (30)	31 (23)
2	65 (48)	81 (60)	73 (54)	47 (35)	65 (48)	57 (42)	22 (16)	36 (27)	31 (23)
3	56 (41)	68 (50)	61 (45)	33 (24)	41 (30)	35 (26)	16 (12)	23 (17)	19 (14)
4	46 (34)	74 (55)	62 (46)	38 (28)	60 (44)	50 (37)	11 (8)	20 (15)	14 (10)

Table 9—Crack Opening Displacement (COD) Test Results—Critical COD, mm (in.)

Weld number, consumables	Test location	Testing temperature		
		−4°C (+25°F)	−23°C (−10°F)	−51°C (−60°F)
(1) 8010/8010	Weld metal	0.216 (0.0085)[a]	0.196 (0.0077)	0.244 (0.0096)
		0.249 (0.0093)	0.234 (0.0092)	—
	HAZ	0.107[c] (0.0042)	0.683 (0.0269)	0.127[c] (0.0050)
		0.450 (0.0177)	0.096[c] (0.0038)	0.508 (0.0200)
	Root passes	0.183 (0.0072)	0.264 (0.0104)	0.102 (0.0040)
		0.193 (0.0076)	—	—
(2) E70S-1B/8010	Weld metal	0.234 (0.0092)	0.178 (0.0070)	0.218 (0.0086)
	HAZ	0.234 (0.0092)[a]	0.206 (0.0081)	0.290 (0.0114)
		0.528 (0.0208)	0.264 (0.0104)	0.269 (0.0106)
	Root passes	0.294 (0.0116)	0.190 (0.0075)	0.168 (0.0066)
		—	0.325 (0.0128)	—
(3) E70S-1B/8018-C1	Weld metal	0.549 (0.0216)	0.528 (0.0208)	0.368 (0.0145)
	HAZ	0.493 (0.0194)	0.592 (0.0233)	0.127[c] (0.0050)
		—	0.175 (0.0069)	0.224 (0.0088)
	Root passes	0.179 (0.0070)	0.343 (0.0135)	0.350 (0.0138)
		0.617 (0.0243)	—	—
(4) E70S-1B/LB86-VU	Weld metal	0.312 (0.0123)	0.323 (0.0127)	0.339 (0.0133)
	HAZ	0.467 (0.0184)	0.498 (0.0196)	0.163 (0.0064)
		—	0.450 (0.0177)	0.406 (0.0160)
	Root passes	0.160 (0.0063)	0.221 (0.0087)	0.112 (0.0044)
		0.097[c] (0.0038)[b]	—	—

[a]Porosity.
[b]Lack of fusion.
[c]Duplicate specimen exceeded 0.15 mm (0.006 in.) reference value.

length of precracking was determined after COD testing by fracturing the samples and measuring the actual crack length.

The bend test fixture satisfies the requirements of ASTM E 399 for fracture mechanics testing. The specimen, clip gauge and bend test fixture were immersed in a tank containing methanol and solid carbon dioxide which was used to maintain the test temperature.

Implant Test. The implant test[3] is frequently used to evaluate the hydrogen assisted or cold cracking susceptibility of steels. In this test, a notched bar is incorporated into a weldment in such a way that the material at the root of the notch is raised to a temperature approaching the fusion point of the steel. During the welding process, hydrogen is introduced into the weldment from the cellulosic electrode used to make the deposit. Subsequent loading of the test bar simulates weld restraint which can lead to delayed cracking. This delayed cracking apparently results from hydrogen assisted propagation of cracks initiated at the root of the notch. A relatively high cracking susceptibility would mean that, using the shielded metal arc process, welding of the steel would be difficult due to a high tendency for hydrogen assisted cracking.

For this investigation, the implant test was performed as follows. Cylindrical specimens 5.6 mm (0.22 in.) in diameter were machined with axes transverse to the original rolling direction. One end of each specimen was threaded to apply a load after welding. A helical notch was machined at the other end of each specimen using a special carbide cutting tool. The notch radius and effective cross-sectional area were measured with the aid of an optical comparator. Only those specimens having a root radius of approximately 0.008 mm (0.0003 in.) were used for implant testing.

In the test, the notched end of the specimen is inserted into a hole drilled in a 14.5 mm (0.57 in.) thick mild steel plate. The test weld is then deposited down the center of the plate, fusing in the notched end of the specimen. The test weld is deposited manually but a guide is used to control travel speed. By this method, the heat input is held within about 8% of the average value. The welding parameters used are given in Table 4.

The welded surface of the implant test assembly was placed in water exactly 2 min after the test weld was completed and held in contact with water for 4 min. The test assembly was removed from the water 6 min after completion of the test weld and loaded in a modified creep testing machine 10 min after completion of the test weld. Welded specimens of each steel were subjected to various loads for 1000 min or until failure occurred. The critical stress was determined graphically. The applied stress was plotted against log time to failure, and the lower limit of the scatter band that asymptotically approached a horizontal line was taken as the critical stress.

Other Tests. The transverse weld tensile tests, base metal tensile tests and bend tests were conducted according to API Specification 1104. For metallographic examination, se-

lected specimens were mechanically polished and etched with 2% nital. Microhardness traverses were made through the various weld deposits and HAZ regions. The readings were taken at intervals of 0.25 mm (0.010 in.). A Vickers indenter with a 1 kg (2.2 lb) load was used for the hardness impressions.

Results

The results of the mechanical tests were interpreted using both the API 1104 specification and the specifications of Foothills Pipe Lines (Yukon) Ltd.[4] However, due to the limited amount of material available, it was not always possible to test the number of specimens required.

Radiographic Examination

The results of the radiographic examination are shown in Table 5. The numbers indicate the approximate relative position around the circumference starting at the top of the weld and progressing around the pipe. Verbal descriptions of discrepancies visible in the radiograph are given. The severity was interpreted by a technician having American Society for Nondestructive Testing (ASNT) Level II nondestructive evaluation qualifications. Conformance or nonconformance to the API 1104 specification is noted for each discrepancy.

Based upon these results, weld 1 (8010 root and 8010 fill) and weld 2 (E 70S-1B root and 8010 fill) failed the API requirements. Weld 3 (E 70S-1B and 8018-C1) passed, but weld 4 (E-70S-1B and Kobe LB-86VU) also failed. The defects in welds 1 and 2 consisted of large areas of lack of penetration and/or fusion along with some porosity in the fill passes. Weld 4 had similar defects although to a lesser extent.

Since no evidence of cold cracking was detected, it was concluded that the majority of defects found in these simulated field welds were, in reality, welder-related. More experienced operators skilled in the use of each particular consumable could be expected to make sound welds without these defects. For this reason, it was decided to continue with this investigation of the weldments, using selected areas containing sound weld metal to evaluate the mechanical properties of the weld region. Unfortunately, the attempt to obtain sound weld samples was not always successful. This is discussed in a following section.

Drop Weight Tests

The drop weight test results are presented in Table 6. All welds passed the test at −4°C (+25°F) and at −23°C (−10°F), the latter temperature being somewhat below the Foothills specification. At a still lower temperature, −51°C (−60°F), welds 1 and 3 passed, but 2 and 4 failed.

Bend Tests

Bend test results are also shown in Table 6. Two root and face bend tests were performed for each weld. Weld 3, the low-hydrogen vertical-up weld, passed all four tests. Each of the other welds had one sample that failed. Welds 1 and 2, the cellulosic electrode welds, each had one face bend specimen fail. Weld 4, a weld made using the E 70S-1B electrode, failed one root bend specimen.

These results are understandable when the radiographic results are considered. Regardless of the attempts to select areas of sound weld metal, small defects still influenced the results of the drop weight, bend and nick-break tests.

Nick-Break Test

All weldments passed this test with the exception of weld 4—Table 6. This failed due to a lack of fusion.

Tensile Tests

Table 7 shows the results for the weld metal tensile tests. These results meet the requirements for the Foothills specification.

Charpy V-Notch (CVN) Test

Two sets of specimens were evaluated. One set, evaluated by the electrode manufacturer, consisted of five samples selected at each test temperature to examine the notch toughness of the weld metal in the region of the filler passes. The second set of specimens was selected from the root and hot-pass area and HAZ of the pipe in addition to the filler passes.

The second set of samples was evaluated by Climax. Due to the small amount of material available, only two specimens were tested at any one location. The Climax data are presented in Figs. 4 to 7 and show both the impact energy absorbed as well as the fracture appearance as a function of test temperature. The samples designated as root weld specimens were taken from the root and hot pass zone; however, they may contain some material from the fill pass zone due to the attempt to obtain a full-sized CVN sample from the small root zone. The HAZ specimens were positioned in the weldment so that the notch would be predominantly in the coarse grained region of the HAZ. The weld metal samples were positioned to one side of the center of the weld deposit. For all specimens the notch was oriented perpendicular to the pipe wall and crack propagation was in the welding direction.

The Charpy toughness requirement specified by Foothills, against which the results of this study are compared, is 51 J (38 ft-lb) as an average of three specimens with no specimen being lower than 39 J (29 ft-lb). The same temperatures were used as for previous tests.

The results obtained by the electrode manufacturer, shown in Table 8, indicate that the weld metal for all four weldments passed at −4°C (+25°F). At −23°C (−10°F) only weld 2, the 70S-1B/8010 weld metal, met the above criteria. At −51°C (−60°F), which is well below the Foothills minimum design temperature, none of the weld deposits were above the minimum toughness requirement. The Climax results are similar to the above data in that all weld zones passed at −4°C (+25°F). With the exception of one of the two HAZ specimens for weld 4, all weld zones failed at −51°C (−60°F). At −23°C (−10°F) the results are mixed.

Typically, the HAZ showed the greatest impact toughness, passing for all welds. The root passes made using the E 70S-1B electrode showed the lowest impact toughness, failing for welds 2, 3 and 4. The root welded using the cellulosic electrode, weld 1, had one passing and one failing CVN specimen. For the filler metal passes, welds 1 and 4 had both specimens pass, while for welds 2 and 3, one specimen passed and one specimen failed.

The Climax results illustrate only the general trends in the toughness performance of the various weld zones and interpretations must be made with caution. Due to the heterogeneous nature of a weld, some variability of results is to be expected. A larger sample size than was available for this study would be necessary to determine the suitability of a certain consumable or process.

Crack Opening Displacement (COD) Test

Samples were taken so that the area examined would be in the HAZ, fill or root passes. The precrack in the HAZ specimens was placed so as to attempt to cross the fusion line. For the other two specimen groups, the precrack was placed in either the filler or root deposits as applicable. The results are presented in Table 9.

No value for critical COD is currently specified; thus it is not possible to define a pass/fail criterion. However, as a reference point, the number most frequently cited is 0.15 mm (0.006 in.).

Based upon this value virtually all of the specimens "passed." For many of the various weldment/temperature combinations, two tests were performed. This was especially true if the first measured COD value was less than 0.15 mm (0.006 in.). Due to a lack of materials, duplicate tests were not possible at all temperatures.

Microhardness Test

A graphical plot of Vickers hardness vs. relative position in the weldment is shown in Fig. 8. It compares the five areas of interest in this investigation. It should be noted that a 1 kg (2.2 lb) load was used for the microhardness tests, as has been the practice at Climax. The Foothills specification calls for a 0.5 kg (1.1 lb) load and requires that no area should have a microhardness greater than 350 HV0.5.

The maximum hardness for all welds was well below the allowed maximum so that the differences in loads should not be significant. The base metal hardness of the X-70 pipe was about 214 HV1. Thus it may be seen that the traverse did not go completely out of the HAZ and into the base metal; however, the area of maximum hardness was crossed.

Implant Test

The lowest applied stress (critical stress) that resulted in the failure of an implant specimen was 220 MPa (32 ksi)—Fig. 9. This implies a CS/UTS ratio of 0.34.

This value is somewhat lower than that obtained for pipeline steels of similar composition. However, it is significant to note that even with this value, no hydrogen assisted cracking was detected, even though no preheating of the pipes was performed. Since usual field practice is to preheat prior to welding, hydrogen assisted cracking should not be a problem with the low-carbon Mo-Nb steel.

Metallography

Photomicrographs of the weldments are shown in Figs. 10 to 15. Figure 10 shows the microstructure of the Mo-Nb X-70 pipe steel. It consists of a mixture of polygonal ferrite, pearlite and upper bainite. A large fraction of the ferrite has been deformed by controlled rolling of the pipe skelp below the Ar_3 temperature. This controlled rolling procedure results in a rounded stress-strain curve with an appreciable work hardening rate, so that the formed pipe has a higher yield strength than the skelp. This offsets the loss in yield strength due to the Bauschinger effect that occurs during testing of a flattened API tensile specimen.

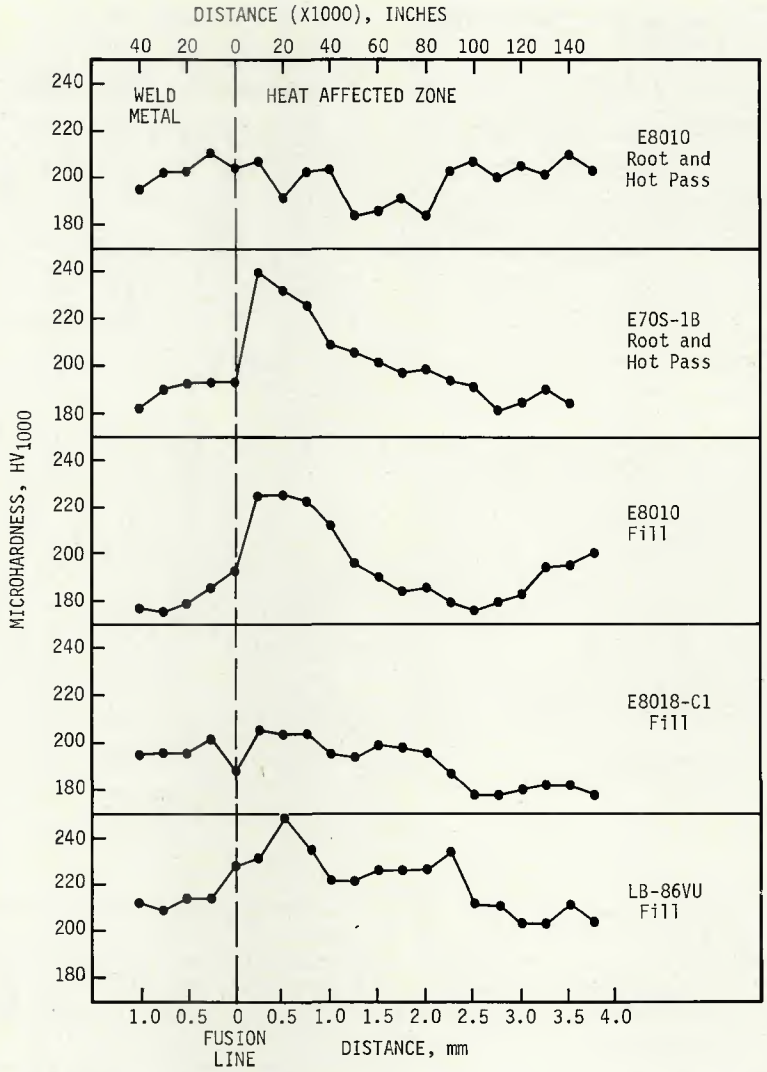


Fig. 8—Microhardness of weld and HAZ

Figure 11 shows the structure of the root pass made using the 8010 electrode. It consists of a very fine polygonal ferrite with pearlite. Figure 12 shows the structure of the fill passes made using the same electrode. The microstructure is the same.

Figure 13 shows the structure of the weld made using the 8018-C1 electrode. It is mainly acicular ferrite and polygonal ferrite with scattered mar-

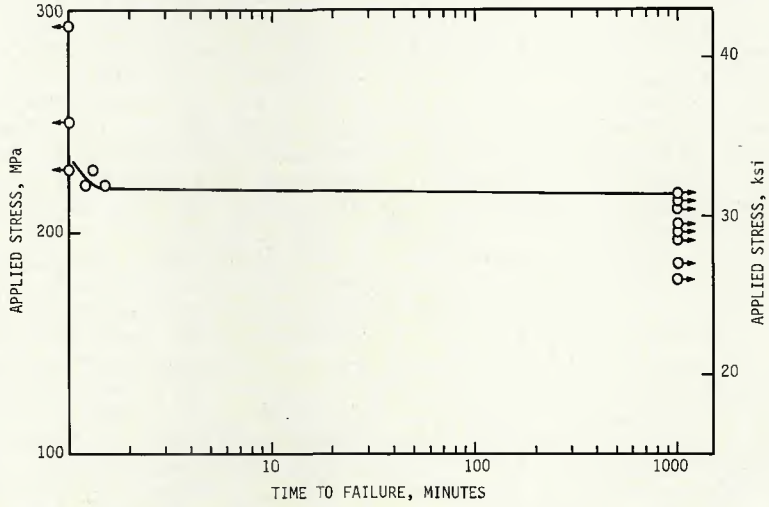


Fig. 9—Implant test results

Fig. 10—X-70 pipe steel base metal. 2% nital, ×500 (reduced 45% on reproduction)

Fig. 12—E8010 cellulosic electrode, fill pass. 2% nital, ×500

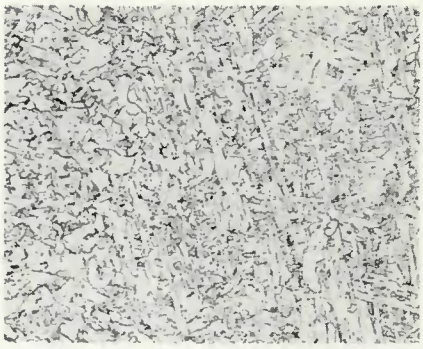


Fig. 14—Kobe LB-86 VU low-hydrogen vertical-down electrode. 2% nital, ×500

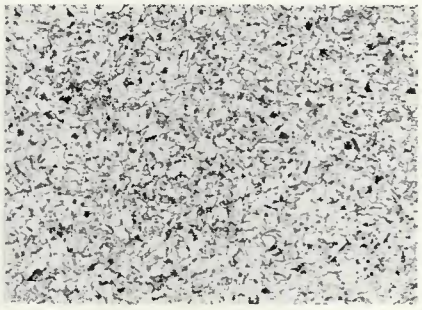


Fig. 11—E8010 cellulosic electrode, root pass. 2% nital, ×500 (reduced 45% on reproduction)

Fig. 13—E8018-C1 low-hydrogen vertical-up electrode. 2% nital, ×500

Fig. 15—E70S-18 GMAW electrode, root pass. 2% nital, ×500

tensite islands. Figure 14 shows the structure of the weld made using the Kobe electrode. It consists of acicular ferrite with small martensite islands. Figure 15 shows the microstructure of the E70S-1B used for the GMAW root passes. This microstructure is predominately acicular ferrite with many small martensite islands. A few round silicate inclusions may be seen. These inclusions may have reduced the toughness of this weld.

Discussion

Based upon the results of the tests performed, weldments made using any of the four consumable/process variations would be suitable, for the most part, for service at −4°C (+25°F) as specified by Foothills. The reason for qualifying this statement is due to the results of the bend and nick-break tests (both of which are more dependent on operator technique than on the consumables used). This service temperature applies to 98% of the Canadian portion of the pipeline.

At −23°C (−10°F), the test results were mixed. It is possible that increases in impact energy absorption at this temperature may be achievable without excessive efforts. Again, weld quality should improve with better operator skill and also through the use of improved consumables.

As stated previously, all personnel making the welds were skilled welders. However, the results of the radiographs and examination of selected samples obtained from several sets of tests indicate that the welds were not of optimum quality. It became apparent that a welder required a certain amount of practice with an unfamiliar consumable before his usual high level of quality could be achieved.

Unfortunately, the amount of practice required, in some cases, proved to be more than was available. This is especially true for weldments 1, 2 and 4. Weldment 3, the low-hydrogen vertical-up weld seemed to present few welding difficulties judging by the radiography results. Weld 4, the Kobe low-hydrogen vertical-down weld, exhibited porosity problems due to the welder using an inappropriate starting and stopping procedure.

The correct procedure was developed by trial and error, but this experimentation was conducted in the weldment to be evaluated. Welds 1 and 2, the cellulosic welds, were intended to serve as a base for comparing the other consumables. It became apparent that, even though the welders used similar cellulosic electrodes in their work, the different arc characteristics required a slightly different method of manipulating the electrode as the weld progressed. Again, due to lack of material, the learning was obtained on the weld which was evaluated. The severity of this problem was not evident until the welds were completed and the radiographs interpreted.

Because of these weld quality problems, which would not exist if proper training time were available, the results of the mechanical tests may be too conservative. Thus, the CVN test results at −23°C (−10°F) on the weld deposits should be interpreted with some flexibility. The above comment should also be kept in mind when considering the three bend tests, the one nick-break and possibly the two dropweight test failures at −51°C (−60°F).

Further improvements of welding consumables could be efficacious. The four consumables evaluated in this investigation were selected because these materials were readily available and were of practical interest. Based upon the results of this study, other consumables should be tested and compared to see if they offer improvements in either ease of welding or mechanical properties.

It was shown that the HAZ of the Mo-Nb X-70 pipe exhibited acceptable properties down to at least −23°C (−10°F)—that is, the microhardness was within specification, the COD values generally exceeded 0.15 mm (0.006 inches) even at −51°C (−60°F), and HAZ apparently is not a problem as evidenced by the implant test and welding the pipe without preheat. Even though the actual weld deposits examined in this study were not com-

pletely acceptable at −23°C (−10°F), the low-carbon Mo-Nb X-70 pipe steel, as evidenced by the acceptable HAZ toughness properties, appears to meet the requirements for Arctic pipelines.

Conclusions

Extensive testing was performed on a series of Mo-Nb X-70 steel pipe weldments made using SMA and GMA welding techniques and four electrode combinations. The evaluation criteria were the API 1104 and Foothills Pipe Lines (Yukon) Ltd. specifications.

It was found that all weldments met the requirements for service at −4°C (+25°F). While the X-70 pipe exceeded the lower temperature requirements, the weld deposits showed mixed results at −23°C (−10°F). These welds would probably pass all requirements at −23°C (−10°F) if weld quality were optimized. It would appear, however, that better welding techniques and/or consumables should be investigated aiming to come up with improved weld performance at −23°C (−10°F).

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