

Effect of Welding Parameters and Electrode Condition on Alloying Enrichment of Weld Metal Deposited with Coated Cellulosic Electrodes

The effect of welding parameters and dried condition of cellulosic electrodes on C, Si, and Mn enrichment as well as increased cracking susceptibility of deposited weld metals were evaluated

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ABSTRACT

Manual welding with cellulosic electrodes is widely used. However, unexpectedly high weld metal alloy contents have been associated with weld metal hydrogen-assisted cracking. Lot-to-lot consumable variation may not always be the primary factor responsible for unexpected cases of highly alloyed weld metals. Therefore, the effect of welding parameters (arc length, welding current, and weld length) and conditions of the cellulosic electrode (as-received and dried) on alloying enrichment of deposited weld metals were evaluated. Arc length, weld length, and “dried” condition of the electrode have a primary effect on the chemical composition of deposited weld metals. Welding current has a secondary effect. Decreasing the arc length resulted in an increase of carbon level in the weld metal. A large increase in manganese and silicon in the weld metal resulted with increasing distance from the weld start point or the use of cellulosic electrodes in the “dried” condition. Alloying enrichment of the weld metals, as indicated by the carbon level and carbon equivalent, results in an increase in susceptibility of the weld metal to cracking.

Introduction

Despite advances in mechanized welding technology, development of low-hydrogen self-shielded flux cored arc welding (FCAW-S) consumables, and substantial improvement of basic low-hydrogen downhill shielded metal arc welding (SMAW) electrodes, manual welding with cellulosic electrodes is still widely utilized throughout the world. Cellulosic-coated SMAW electrodes (AWS EXX10, EXX11) are traditionally used for “stovepipe” welding of pipelines because they are well suited for deposition of pipeline girth welds and are capable of high deposition rates when welding downhill.

Cellulosic electrode coverings typically contain silicate binders, 30 to 45% cellulose ($C_6H_{10}O_5$)_n, 15 to 20% rutile (TiO_2), extrusion aides, and ferro-alloy additions (Refs. 1–3). During production, these electrodes are typically “dried” (70° to

150°C [158° to 300°F]), not baked, after extrusion. During welding, decomposition of the cellulose and water generate carbon monoxide (CO) and hydrogen gas that shield the weld pool, surrounding the weld pool with reducing conditions. Hydrogen gas causes the resistance of the arc opening to increase, which results in a higher arc voltage and a more penetrating arc (Ref. 3). However, the resulting diffusible hydrogen level in weld metal deposits produced using cellulosic electrodes is high (30 to 60 mL H₂/100 g deposited weld metal), which restricts the use of cellulosic electrodes on high-strength steels or when welding thick sections with high restraint.

Hydrogen-assisted cracking (HAC) remains one of the most important technical issues associated with manual girth welding of pipelines when using cellulosic electrodes. Some reviews provide examples of HAC, which has occurred in pipeline girth welds and the economic impact associated with HAC (Refs. 4, 5). In one case, cracking was attributed mainly to rich weld metal (0.19 wt-% C, 0.5 wt-% Mo) deposited using E7010-G electrodes and hard regions that formed due to undissolved molybdenum particles originating from the electrode covering. In another case, cracking was attributed to on-site modification of the weld procedure allowing deposition of thin, low-heat-input stringer passes with low interpass temperature, and the use of higher carbon equivalent welding consumables.

However, in other reported cases of HAC (Ref. 6), even though established welding procedures were used, it was clear that richer than expected weld metals were deposited and played a critical role in the resulting observed cracking. Several factors that can contribute to rich weld metal compositions include dilution from the base metal, lot-to-lot consumable variation, welding parameters (arc length, current) within the operating window, and factors that influence weld metal transfer mode such as covering moisture and perhaps power supply characteristics.

This experimental work evaluated possible effects of lot-to-lot consumable variation, welding procedure variation, and covering moisture on alloying enrichment of weld metals deposited with cellulosic-coated electrodes.

Experimental Approach

Three sets of experiments were conducted to evaluate the potential alloying enrichment of the weld metal as a result of lot-to-lot consumable variation, welding parameter variation (arc voltage, welding

KEYWORDS

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Weld Length
As-Received and “Dried”
Conditions

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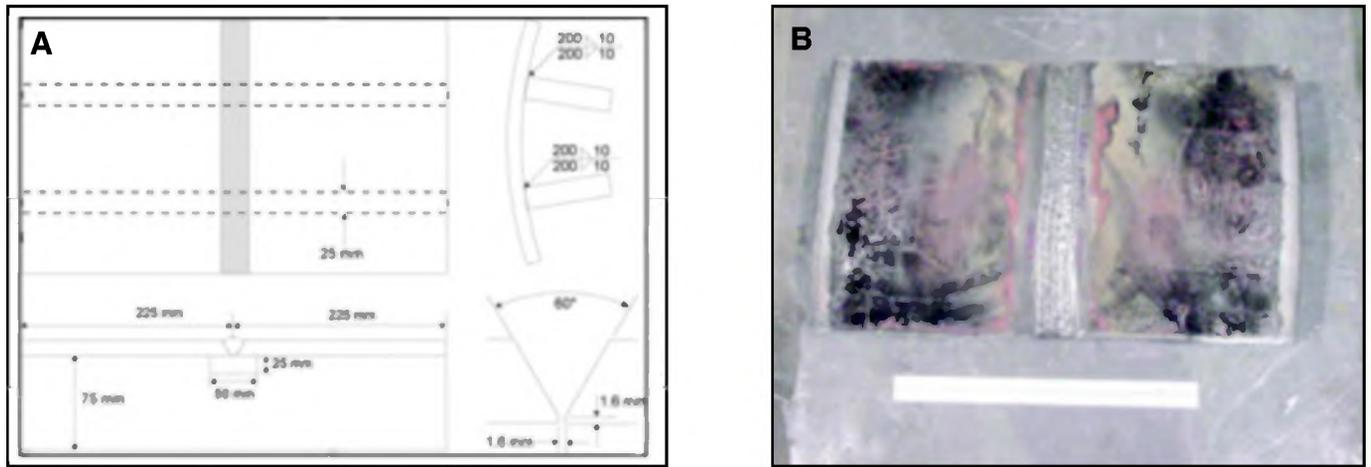


Fig. 1 — Multipass weld assembly using a section of 36-in.- (914-mm-) diameter X70 pipe. A — Schematic illustration; B — picture.

current, and weld length), and covering moisture.

Failure Analysis of Cracked Welds

Welds representing three cases, identified as A, B, and C, where cracking was observed in the field, were obtained from industry and used for analysis. In all three cases, significant transverse cracking was observed, and the same type of consumable (AWS E8010-G) from different lot numbers from the same manufacturer was used (Ref. 6).

The chemical composition of the weld metals and pipe materials representing the cracked joints from the three different cases was determined. Additionally, unconsumed electrodes from the lot used to deposit the cracked welds in case C were returned to the manufacturer for evaluation. Nominal weld metal composition data from the certificate of conformance tests corresponding to the time interval for the production of consumables used in case C were obtained as well.

Finally, a small number of electrodes with identical production codes to those used to produce the cracked girth welds in case C were used for evaluation. Chemical analysis test pads were produced following instructions prescribed in AWS A5.5/A5.5M:2006, *Specification for Low-Alloy Steel Electrodes for Shielded Metal Arc Welding* (Ref. 7). Duplicates of the chemical analysis test pads were conducted at the consumable manufacturer. The weld pads for chemical analysis were produced using welding currents of 120 to 130 A, 23 V for the 4.0-mm- ($\frac{1}{2}$ -in.-) diameter electrodes, and 160 to 170 A, 24 V for the 4.8-mm- ($\frac{3}{8}$ -in.-) diameter electrodes. The results from this failure investigation established the basis for additional testing as described below using a

separate lot of commercially procured E8010-G electrodes from the same manufacturer.

Welding Parameter Variation

In order to evaluate the effect of welding parameter variation (arc voltage, welding current, and weld length), standard AWS A5.5/A5.5M:2006 instructions and groove weld test assembly were utilized. A 0.75-in.-thick carbon steel plate was used as the base material. A 4.8-mm- ($\frac{3}{8}$ -in.-) diameter E8010-G electrode was used to deposit the experimental welds in the flat position with short (1 mm), medium (2–3 mm), and long (5 mm) arc lengths and a range of welding currents. An inverter power supply and a single lot of electrodes were used. The summary of the welding conditions used is listed in Table 1.

The chemical compositions of the welds were measured in the cap region of the weld deposits, in longitudinal sections along the centerline of the weld, at locations about 3 in. (76.2 mm) from the start of the weld beads. In some of the welds, the effect of weld length (welding time) or position relative to the weld start on weld metal chemical composition was evaluated. Chemical composition of the weld metal was determined at locations about 1.5 in. (38.1mm) (near the start of the weld) and 5.0 in. (127.0 mm) (near the end of the weld) from the start of the weld.

Covering Moisture

One key observation in the failure analysis mentioned above was that all cracked welds were produced in field conditions where high temperatures were

Table 1 — Summary of Welding Parameters Used in Procedure Variation Evaluation

Electrode/ Preheat/ Interpass	Base Metal /Position	Arc Length	Heat Input (kJ/mm)	Voltage (V)	Current (A)
E-8010G 4.8 mm ($\frac{3}{8}$ in.) ϕ / 16°C (60°F)/ 149°C (300°F)	Plate $\frac{3}{4}$ " (19.0mm) thick/ flat	Short (1 mm)	1.1 to 1.8	26.5	145
			26.0	145	
			27.0	165	
		27.5	172		
		29.0	200		
		30.0	200		
	Medium (3 mm)	1.5 to 2.3	30.0	200	
		30.0	143		
		31.5	171		
	Long (5 mm)	1.7 to 2.5	35.0	199	
			35.0	199	
			35.0	172	
			38.0	172	
			38.0	172	

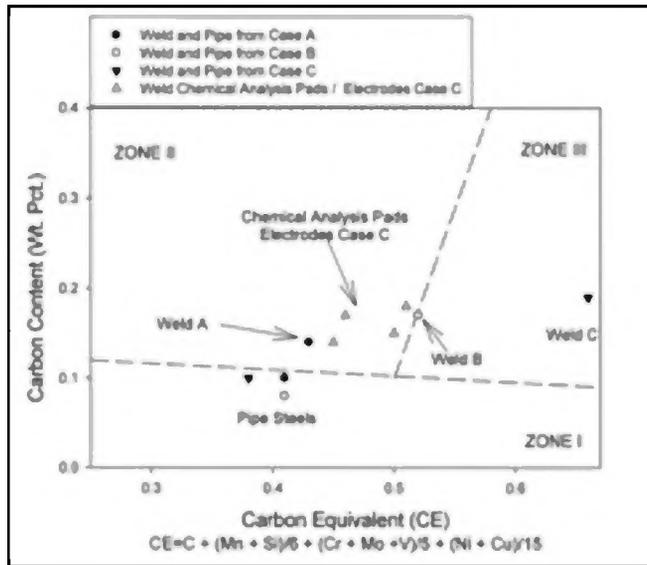


Fig. 2 — Carbon and carbon equivalent of weld metal and pipe corresponding to cases A, B, and C, and measured in AWS chemical analysis test pads made using retained electrodes from case C.

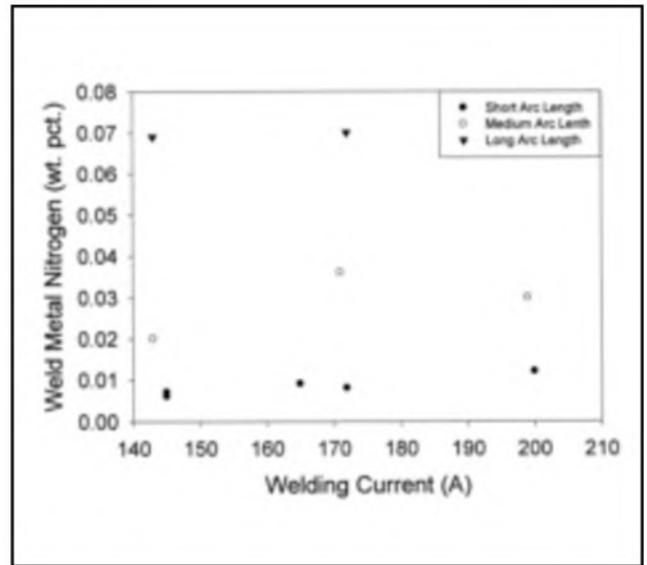


Fig. 3 — Weld metal nitrogen concentration as a function of welding current and arc length (short, medium, and long).

present. Therefore, it was possible that electrodes were subjected to elevated temperatures for long periods of time. In order to understand how electrode handling and storage conditions might impact composition in a pipeline girth weld, additional experiments were carried out to evaluate how additional drying of cellulosic electrodes would impact chemical composition of a multipass weld deposit.

Groove welds were produced using as-received 4.8-mm- (3/16-in.-) diameter E8010-G electrodes and electrodes of the same batch that had been stored in a bak-

ing oven at 86°C (187°F) for a period of 1 week prior to welding. The moisture content of the electrode was not measured but similar drying conditions resulted in a 53 to 88% decrease in moisture content of E8010 cellulosic electrodes with as-received moisture content ranging from 1.64 to 4.09 wt-% (Ref. 8). The experimental welds were deposited in sections of 36-in.- (914-mm-) diameter API X70 pipe of 12 and 19 mm (0.472 and 0.748 in.) thickness as the base metal. A schematic illustration of the multipass pipe test fixture and photograph of a completed specimen are

shown in Fig. 1. A typical welding procedure used to deposit the groove welds is listed in Table 2.

The chemical composition of the deposited weld metals was determined following the same procedure as described in the welding parameter variation section. Additional experimental welds were produced using the same lot of electrodes, and the arc signal and metal transfer was characterized using high-speed data acquisition and high-speed video.

Results and Discussion

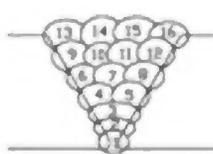
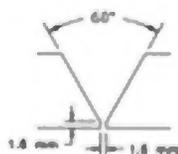
Failure Analysis of Field Welds

The composition and carbon equivalent (Ref. 9) of the weld metal and pipe material representing the cracked joints from cases A, B, and C are listed in Tables 3 and 4. The carbon and carbon equivalent measured in welds containing cracks and the pipe materials are plotted in a map of carbon content vs. carbon equivalent (Ref. 9) shown in Fig. 2. Weld metals from cases B and C show the highest alloying levels as described by the carbon and carbon equivalent. The weld metal B had a carbon concentration of 0.17 wt-%, manganese concentration of 1.40 wt-%, and a carbon equivalent of 0.52 wt-%. Exceptionally high manganese (1.9 wt-%) and carbon (0.19 wt-%) concentrations were measured in the cracked girth weld metal C, resulting in a carbon equivalent of 0.66 wt-%.

The consumable manufacturer reported that the retested electrodes representing the electrodes used in case C deposited weld metals were within

Table 2 — Welding Procedure Used in Evaluation of the Effect of Electrode Condition

	Condition Description	Pass	Volts (V)	Amps (A)	Weld Time (s)
Electrode:	E-8010G	1	28.1	79	148.7
	3.2 mm (1/8 in.) ϕ root	2	28.8	171	61.4
	4.8 mm (3/16 in.) ϕ	3	28.5	176	83.0
		4	28.5	171	65.7
Preheat:	170°C (340°F)	5	28.8	169	67.8
		6	28.6	169	65.5
Interpass:	170°C (340°F)	7	28.2	172	56.9
		8	28.5	169	71.9
Base Metal:	3/4 in. (19.0 mm) thick X70 plate	9	28.7	169	68.8
		10	29.5	167	60.6
Welding Position:	Flat	11	28.7	170	55.0
		12	29.4	165	53.0
		13	30.3	163	67.7
Technique:	Stringer	14	29.8	165	58.3
		15	29.5	165	60.7
		16	28.6	168	67.6



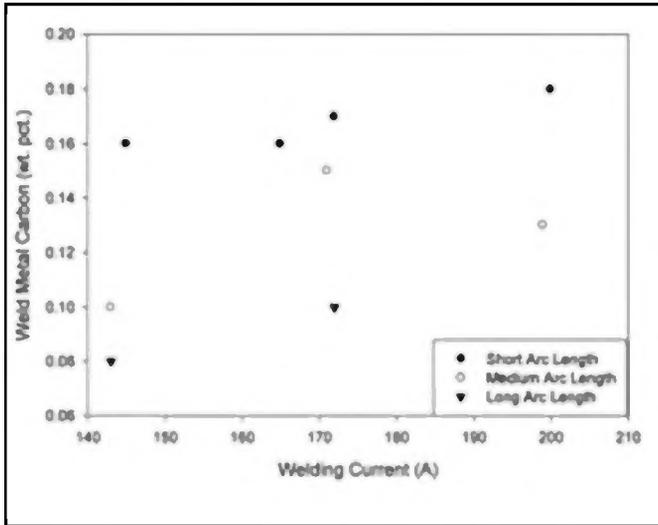


Fig. 4 — Weld metal carbon concentration as a function of welding current and arc length (short, medium, and long).

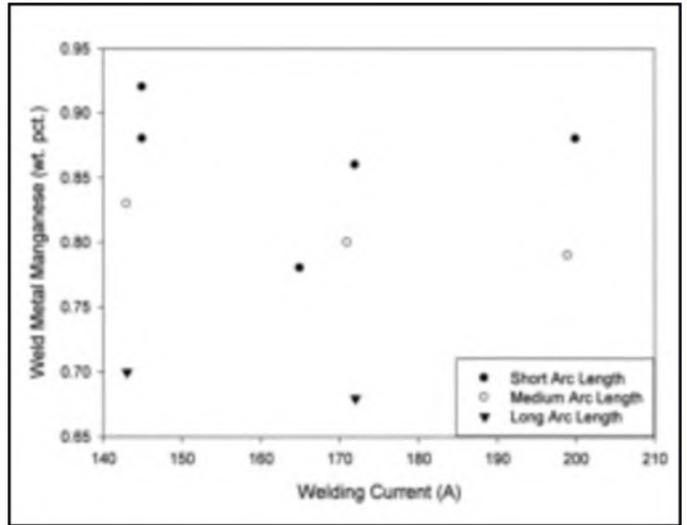


Fig. 5 — Weld metal manganese concentration as a function of welding current and arc length (short, medium, and long).

established manufacturing ranges. Nominal weld metal compositions from certificate of conformance tests corresponding to the time interval for the production of the consumables used in case C is summarized in Table 5. As indicated in Tables 3 and 4, AWS 5.5/A5.5M:2006 specification does not include limits for carbon levels in all-weld metal deposited with E8010-G electrodes. Compared to the weld metal composition reported in the certificate of conformance test welds, the manganese concentration in the case C welds was substantially higher. Silicon was slightly higher than the typical conformance test welds while other elements such as nickel and molybdenum were representative of the weld metal composition expected from electrodes produced during that time period.

The compositions of the chemical analysis weld pads produced in-house and weld pads duplicated by the consumable manufacturer, representing the consumable used in case C, are included in Table 4. The composition measured in the weld pads was close to the values reported in the certificate of conformance test results. Slightly richer composition was measured in the weld pads produced with the 4.8-mm- (3/16-in.-) diameter electrodes. Although the chemical analysis pad welds were relatively rich, the high manganese (1.9 wt-%) and high silicon (0.29 wt-%) concentrations measured in the field girth welds from case C, and the resulting high carbon equivalent were not duplicated, as shown in Fig. 2.

The level of lot-to-lot variation is an open question and an area of continuous

improvement for all electrode manufacturers. Many electrode manufacturers have developed elaborate controls to ensure that a consistent product is produced. For example, specifications are often placed to control core wire composition, flux composition (this is usually analyzed in each lot), and covering thickness.

As a summary, the weld metal compositions measured in the E8010-G welds, which exhibited cracking in the field, indicate that a relatively rich composition was present in all three cases, most notably in cases B and C. However, direct comparison of results from electrode retesting,

certificate of conformance testing, and from analyses of weld pads representing consumables used in case C with the composition of the cracked girth welds does not substantiate the high manganese and silicon concentrations. Additionally, as presented in following sections, the chemical composition of E8010-G welds deposited with a separate lot of commercially procured E8010-G electrodes from the same manufacturer and using standard welding parameter conditions and/or electrodes in the as-received condition was much leaner than those of the failed welds from case B or C.

Table 3 — Composition of Weld Metal and Steel Pipe from Cases A and B (wt-%)

	EXX10-G A5.5 Req.	Case A		Case B	
		Weld	Pipe	Weld	Pipe
C	NS	0.14	0.10	0.17	0.077
Mn	1.00 ^(a)	1.15	1.51	1.40	1.37
P	NS	0.021	0.008	0.011	0.016
S	NS	0.004	<0.001	0.008	0.004
Si	0.80 ^(a)	0.17	0.29	0.22	0.27
Ni	0.50 ^(a)	0.47	<0.10	0.57	0.02
Cr	0.30 ^(a)	0.12	0.02	0.12	0.02
Mo	0.20 ^(a)	0.06	<0.05	0.075	<0.05
Cu	NS	<0.05	<0.05	0.01	<0.05
V	0.10 ^(a)	0.012	0.042	0.012	0.033
Al	NS	<0.01	0.035	<0.01	0.023
Ti	NS	0.01	<0.01	0.014	<0.01
Nb	NS	<0.005	0.035	0.007	0.029
Zr	NS	<0.005	<0.005	<0.005	<0.005
B	NS	<0.0005	<0.0005	<0.0005	<0.0005
CE ^(b)	NS	0.43	0.41	0.52	0.41

(a) For AWS "G" classification only one of the elements designated with "a" must exceed values shown in the table.

(b) CE = C + (Mn + Si)/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15 (Ref. 9).

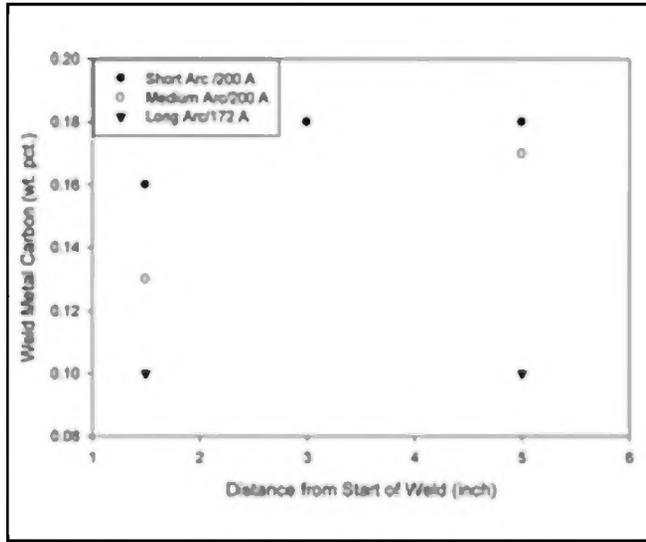


Fig. 6 — Weld metal carbon concentration as a function of weld and arc lengths (short, medium, and long)

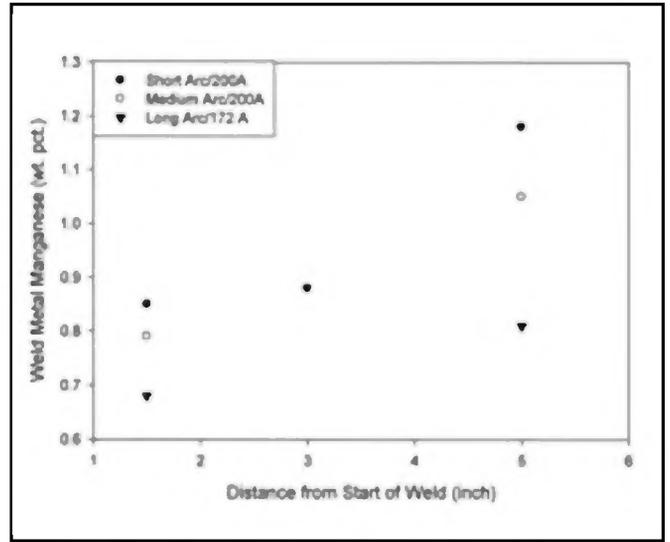


Fig. 7 — Weld metal manganese concentration as a function of weld and arc lengths (short, medium, and long).

Based on the chemical composition of the steel pipe used in the failed welds (Table 4 and Fig. 2), the expected effect of weld metal dilution by the base metal would have been to decrease the carbon and carbon equivalent of weld metal, which is opposite to the high carbon and carbon equivalent observed in welds from case C.

Therefore, these experimental results essentially eliminate lot-to-lot variation in electrode composition as the primary factor responsible for the rich composition measured in these specific cracked weld metals, especially those representing case C, and indicate that other factors must

have contributed to the alloying enrichment measured in these specific cracked girth welds.

Welding Parameter Variation

The results of chemical composition analyses of the weld metal deposited with different welding parameters are listed in Table 6. The base plate chemical composition is also reported in Table 6. Figures 3–5 show the weld metal nitrogen, carbon, and manganese concentration, respectively, as function of welding current and arc length. Important considerations regarding the characteristics of the arc column and weld

metal transfer during SMAW with cellulosic electrodes are needed for the explanation of the observed changes in weld metal chemical composition.

General Characteristic of Arc Column and Weld Metal Transfer with Cellulosic Electrodes

During SMAW with cellulosic electrodes, decomposition of the cellulose and water generate carbon monoxide (CO) and hydrogen gas that shield the weld pool, surrounding the weld pool with reducing conditions (Ref. 2). The reducing conditions are created by the excess of hydrogen and carbon from the cellulose and

Table 4 — Summary of Chemical Composition Measured in Weld Metals from Case C and Results of Chemical Analysis in Welds Pads (wt-%)

	EXX10-G A5.5 Req.	Field Weld		Chemical Analysis Pad			
		Weld	Pipe	EWI 3/16	EWI 5/32	MFR 3/16	MFR 5/32
C	NS	0.19	0.097	0.18	0.17	0.15	0.14
Mn	1.00 ^(a)	1.93	1.35	1.24	0.96	1.33	1.18
P	NS	0.004	0.008	0.004	0.004	N/R	N/R
S	NS	0.007	0.01	0.007	0.007	N/R	N/R
Si	0.80 ^(a)	0.29	0.26	0.16	0.17	0.16	0.13
Ni	0.5 ^(a)	0.64	0.04	0.69	0.75	0.73	0.77
Cr	0.3 ^(a)	0.16	0.04	0.16	0.14	0.15	0.13
Mo	0.2 ^(a)	0.08	0.01	0.08	0.08	0.09	0.09
Cu	NS	0.06	0.01	0.06	0.06	0.01	N/R
V	0.1 ^(a)	0.002	0.006	0.002	0.002	N/R	N/R
Al	NS	<0.01	0.03	<0.01	<0.01	N/R	N/R
Ti	NS	0.01	0.007	0.01	0.01	N/R	N/R
Nb	NS	<0.005	0.01	<0.005	<0.005	N/R	N/R
Zr	NS	<0.005	<0.005	<0.005	<0.005	N/R	N/R
B	NS	<0.0005	<0.0005	<0.0005	<0.0005	N/R	N/R
CE ^(b)	NS	0.66	0.38	0.51	0.46	0.50	0.45

(a) For AWS “G” classification only one of the elements designated with “a” must exceed values shown in the table.

(b) CE = C + (Mn + Si)/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15.

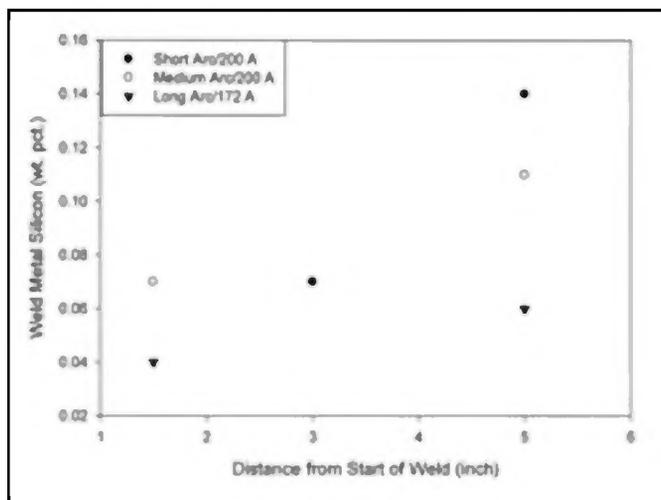


Fig. 8 — Weld metal silicon concentration as a function of weld and arc lengths (short, medium, and long).

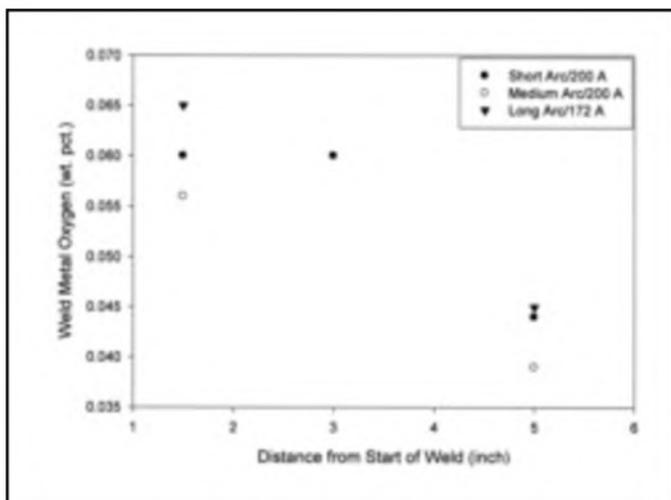


Fig. 9 — Weld metal oxygen concentration as a function of weld and arc lengths (short, medium, and long).

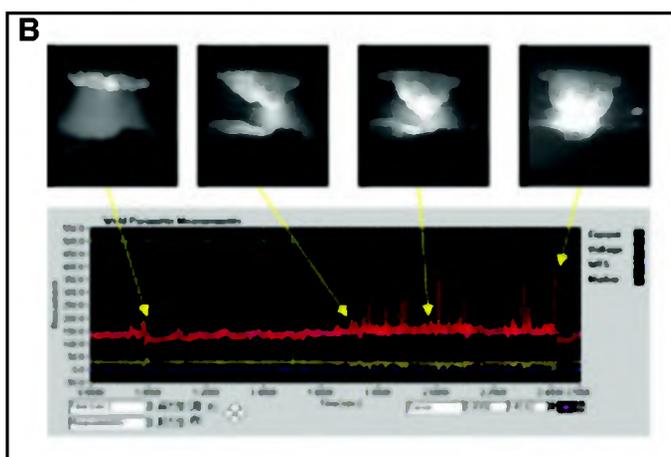
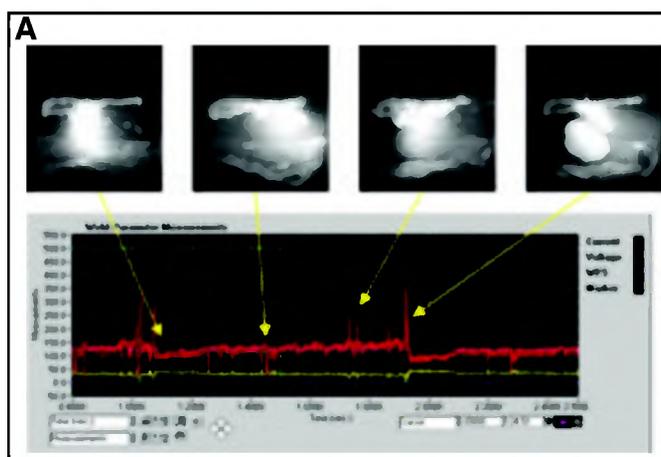


Fig. 10 — Comparison of arc characteristics from as-received and baked E8010-G electrodes. A — Unbaked electrode; B — E8010 baked electrode.

hydrogen from the water. Cellulose has a chemical composition described by the formula $(C_6H_{10}O_5)_n$ with a molar ratio of oxygen to carbon and hydrogen equal to 1:1.2:2.0. The reducing atmosphere of the arc facilitates and increases the efficiency of transfer to the weld metal of not only carbon but manganese and silicon as well (Refs. 10, 11).

The carbon generated during the dissociation of the cellulose may interact with the molten slag during metal transfer and support the silicon-reduction process. This result in the transfer of silicon into the weld metal even if ferrosilicon (FeSi) is not present in the electrode covering. Additionally, due to higher temperature, larger surface area, and nonequilibrium conditions, the rate of oxidation is faster during drop metal transfer than in the weld pool. At the high-temperature con-

dition of the arc (above 2000°C), during weld metal transfer carbon is preferentially oxidized as compare to other elements, which results in a higher transfer of alloying elements to the weld metal.

The potential gradient along the arc length depends on the nature of the cov-

ering and its chemical composition (Ref. 12). Hydrogen gas is a poor electrical conductor and has a high ionization potential that causes the resistance of the arc opening to increase and the electron emission to decrease, which result in a higher arc voltage and a more penetrat-

Table 5 — Summary of Composition Measured in Conformance Welds Deposited during Time Interval when Consumables for Case C Welds Were Produced (wt-%)

	Electrode Diameter		
	3.2 mm (1/8 in.)	4.0 mm (5/16 in.)	4.8 mm (3/8 in.)
Mn	0.91	1.10	1.20
Si	0.25	0.25	0.17
Ni	0.86	0.72	0.70
Cr	0.02	0.11	0.14
Mo	0.08	0.09	0.09
V	<0.01	<0.01	<0.01
Cu	0.02	0.02	0.02

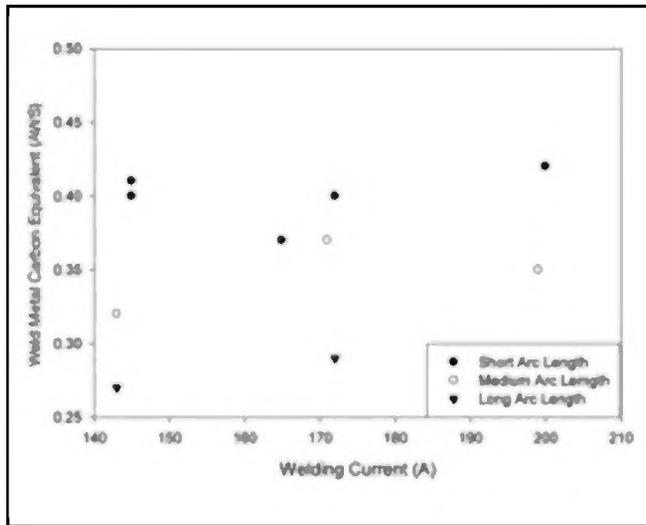


Fig. 11 — Weld metal carbon equivalent as a function of welding current and arc length (short, medium, long).

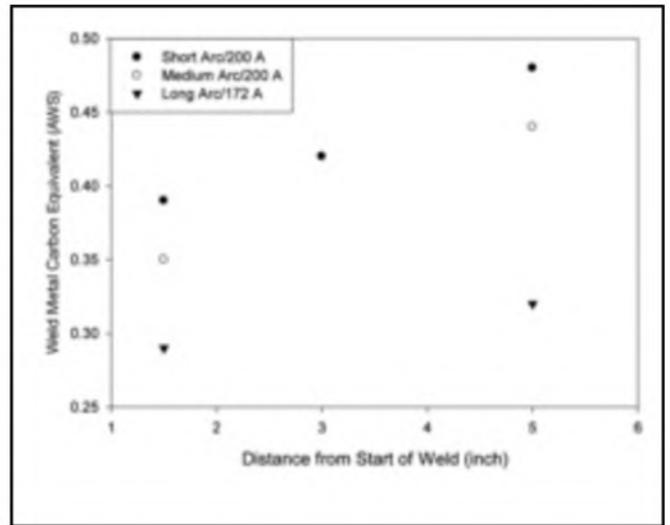


Fig. 12 — Weld metal carbon equivalent as a function of weld and arc lengths (short, medium, long).

ing arc (Ref. 13).

The weld metal transfer across the arc in gas metal arc welding (GMAW) and SMAW is normally described as short-circuit, globular, and spray mode (Refs. 14, 15). In most cases, droplets of various sizes are transferred in the arc, but the type of covering determines the predominant mode of transfer (Refs. 15, 16). The weld metal transfer of cellulosic electrodes has been described as a combination of spray, short-circuit, and explosive transfer (Ref. 17). When welding in the downhill direction, the spray transfer is present all the time, but the metal drops grow periodically and globular transfer

became the dominant mode. In general, gravitation, pinch effect, Lorentz force, and plasma action are less important in SMAW than in welding by other methods unless very high welding currents are used. Forces having a significant effect on SMAW metal transfer include surface tension and viscosity, and metallurgical effects (Ref. 13).

When arc melting killed steel wires in air, oxygen forms an oxide film on the surface of the droplet, oxygen combines mainly with silicon, and this limits the possibility of CO formation, which affects its surface tension rather than causing metal to effervesce. This is characteristic of

welding with basic electrodes, surface tension, and viscosity can determine the metal transfer mode.

During welding with cellulosic electrodes, metal from the melting electrode is usually supersaturated with hydrogen and frequently with CO, which results in its becoming disturbed and effervescent. This affects the melting mode more than surface tension and viscosity do. Additionally, cellulosic electrode coverings contain large amounts of moisture. Electrode coverings usually melt faster than they de-gas. Therefore, large quantities of gas evolve from melting the cellulosic covering, which makes the melting slag effervesce and boil,

Table 6 — Weld Metal Chemical Composition (wt-%) as Function of Welding Parameters

Arc Length	Heat Input (kJ/mm)	Voltage (V)	Current (A)	Carbon	Mn	Si	Ni	Cr	N	O	CE (AWS) (c)
Short	1.1 to 1.8	26.5	145	0.16	0.92	0.10	0.74	0.14	0.006	0.056	0.41
		26.0	145	0.16	0.88	0.08	0.79	0.13	0.007	0.064	0.40
		27.0	165	0.16	0.78	0.06	0.68	0.12	0.009	0.060	0.37
		27.5	172	0.17	0.86	0.07	0.75	0.13	0.008	0.057	0.40
		29.0	200	0.18	0.88	0.07	0.76	0.13	0.012	0.060	0.42
		30.0	200	0.16 ^(a)	0.85	0.07	0.70	0.13	0.015	0.060	0.39
Medium	1.5 to 2.3	30.0	200	0.18 ^(b)	1.18	0.14	0.76	0.14	0.010	0.044	0.48
		30.0	143	0.10	0.83	0.08	0.69	0.12	0.020	0.051	0.32
		31.5	171	0.15	0.80	0.07	0.73	0.13	0.036	0.060	0.37
		35.0	199	0.13 ^(c)	0.79	0.07	0.71	0.13	0.030	0.056	0.35
		35.0	199	0.17 ^(b)	1.05	0.11	0.73	0.14	0.033	0.039	0.44
		35.0	143	0.08	0.70	0.05	0.66	0.11	0.069	0.070	0.27
Long	1.7 to 2.5	38.0	172	0.10 ^(c)	0.68	0.04	0.72	0.12	0.070	0.065	0.29
		38.0	172	0.10 ^(b)	0.81	0.06	0.74	0.13	0.087	0.045	0.32
		—	—	—	0.22	1.10	0.18	0.01	0.04	0.004	<0.003
Base Metal	—	—	—	0.22	1.10	0.18	0.01	0.04	0.004	<0.003	0.44
E8010 ^(d)	—	28–30 (e)	163–170	0.11	0.66	0.10	0.71	0.02	0.021	0.065	0.32

(a) Measured at about 1.5 in. (38.1 mm) from start of weld.

(b) Measured at about 5.0 in. (127.0 mm) from start of weld.

(c) CE = C + (Mn+Si)/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15 (Ref. 9).

(d) Standard welding condition.

(e) Arc length of about 2.5 mm.

and facilitates the transfer of liquid during welding and may promote spray-type metal transfer (Ref. 13).

Effect of Arc Length and Welding Current

As shown in Fig. 3, the weld metal nitrogen content increases from about 100 to about 700 ppm as the arc length is increased. In general, the nitrogen level in the weld metal was not affected by welding current. It may be considered that in addition to affecting the weld metal transfer across the arc column, the effervescence and boiling that results from metallurgical and gas reactions in the melting metal and flux coverings may also act as waves of disturbance that may temporarily disrupt the reducing arc column and its protection to the weld metal from oxygen and nitrogen in the air. The longer the arc length, the higher the degree of disturbance induced in the arc column, which results in a higher probability of mixing with air and in a higher level of nitrogen in the weld metal.

Carbon content in the weld metal increases from about 0.08 to about 0.16 wt-% as the arc length was decreased, as shown in Fig. 4. This represents about a 100% increase in the weld metal carbon content. Increase of carbon in the weld metal with shorter arc length may result from a more stable reaction between the molten weld metal and the reducing or carburizing arc column atmosphere. Even though a longer arc length may represent a longer time for the molten metal-column reaction, the reducing/carburizing potential of the arc column atmosphere may be decreased by a higher degree of disturbance experienced by a long arc column.

These disturbances may even, locally or temporarily, create an oxidizing condition in the arc column atmosphere.

As shown in Fig. 4, at a given arc length, there was a slight increase of carbon content in the weld metal as the welding current was increased. This experimental observation may result from an increase in the rate of weld metal transfer across the arc column due to higher melting rates of the electrodes with higher welding currents (Ref. 18). A higher current causes an increased droplet transfer rate, and consequently, more molten surface area flowing across the arc column per unit of time, which may result in a higher degree of carburization of the weld metal due to reaction with the reducing arc atmosphere.

A similar trend to carbon content in the weld metal, but to a much lower degree, was observed in the manganese content in the weld metal as function of arc length, as shown in Fig. 5. The manganese content in the weld metal changes from about 0.7 to 0.9 wt-%, an increase of about 25%, as the arc length was decreased. With a short arc length, the disturbances of the arc column and the presence of oxidizing species in

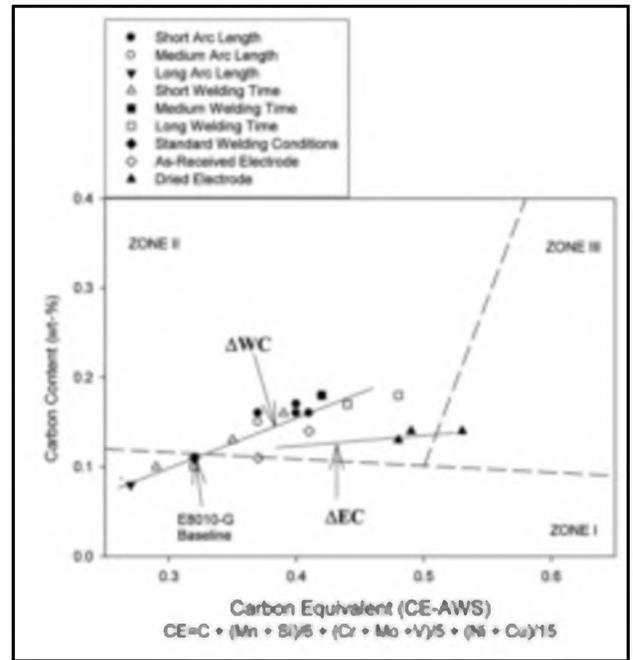


Fig. 13 — Carbon and carbon equivalent changes induced by modifications in welding conditions (ΔWC) or changes in condition of the E8010-G cellulosic electrodes (ΔEC) and resulting increasing susceptibility to cracking observed in weld metals.

the column atmosphere are minimized. Therefore, most of the manganese present as ferromanganese in the flux is recovered in the weld metal. As the arc length increases, the disturbance of the arc column increases, and some of the manganese is consumed in oxidizing/deoxidizing reactions that take place in the arc column or weld metal pool. In general, a similar trend to that observed for manganese in the weld metal was observed for silicon content in the weld metal as a function of

Table 7 — Summary of Weld Metal Composition Measured in the EWI Multipass Mockup Welds Made with As-Received (AR) and Dried Consumables

	12 mm (0.5 in.) 8010-AR	12 mm (0.5 in.) 8010-Dried	19 mm (¾ in.) 8010-AR	19 mm (¾ in.) 8010-Dried	19 mm (¾ in.) 8010-Dried	12 mm (0.5 in.) Base Metal	19 mm (¾ in.) Base Metal
C	0.11	0.14	0.14	0.13	0.14	0.08	0.08
Mn	0.95	1.32	1.00	1.31	1.48	1.60	1.60
P	0.006	0.003	0.007	0.010	0.007	0.008	0.009
S	0.008	0.009	0.010	0.011	0.010	0.003	<0.003
Si	0.12	0.28	0.10	0.28	0.33	0.30	0.31
Ni	0.63	0.60	0.64	0.59	0.62	0.01	0.01
Cr	0.12	0.14	0.13	0.14	0.13	0.02	0.02
Mo	0.07	0.08	0.08	0.08	0.08	0.01	0.01
Cu	0.01	0.01	0.01	0.01	0.01	0.01	0.01
V	0.007	0.010	0.007	0.010	0.007	0.060	0.070
Al	0.02	<0.01	0.02	<0.01	0.02	0.02	0.03
Ti	0.02	0.02	0.02	0.02	0.02	0.01	0.01
Nb	<0.005	<0.005	<0.005	<0.005	<0.005	0.029	0.032
Zr	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
B	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.005	0.0007
CE	0.37	0.49	0.41	0.48	0.53	0.41	0.42

$$CE = C + (Mn + Si)/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15$$

Table 8 — Relative Effect of Arc Length, Welding Current, Distance from the Start of the Weld (Weld Length), and Condition of the Consumable on the Chemical Composition of the Deposited Weld Metals

Element	Decreasing Arc length	Relative Effect on Weld Metal Chemical Composition	Increasing Welding Current	Increasing Distance from Start of Weld	"Dried" Electrode
C	(+++++)	(+)	(+)	(+)	(+)
M	(++)	~	(+++) ^(a)	(+++)	(+++)
S	(+)	~	(+++++) ^(a)	(+++++)	(+++++)
O	~	~	(---)	~	NA
N	(-----)	~	~	~	NA

(+) = Relative increase in the concentration
 (-) = Relative decrease in concentration
 ~ = No effect or definitive trend
 (a) = Specially with high welding current
 NA = Data not available

Table 9 — Summary of Carbon Content and Carbon Equivalent Measured in the Weld Metals as a Function of Arc Length, Weld Length, and Electrode Condition

		Welding Conditions	Carbon (wt-%)	CE
Arc Length (Chemical analysis measured at 3.0 in. [76.2 mm] from start)	Short		0.16	0.41
			0.16	0.40
			0.16	0.37
	Medium		0.17	0.40
			0.18	0.42
			0.10	0.32
Weld Length	1.5 in. (38.1 mm)	Short Arc	0.10	0.37
		Medium Arc	0.15	0.32
		Long Arc	0.18	0.27
	3.0 in. (76.2 mm)	Short Arc	0.08	0.27
		Medium Arc	0.16	0.39
		Long Arc	0.13	0.35
	5.0 in. (127.0 mm)	Short Arc	0.10	0.29
		Medium Arc	0.18	0.42
		Long Arc	0.18	0.48
		Long Arc	0.17	0.44
Standard Condition (about 2.5 mm arc length)			0.10	0.32
Electrode Condition	As-Received		0.11	0.37
			0.14	0.41
			0.14	0.49
	Dried		0.13	0.48
			0.14	0.53
			0.14	0.53

arc length. Even though cellulosic coverings may not contain ferrosilicon, the weld metal may contain some silicon that is reduced from silicates in the covering.

Effect of Weld Length and Welding Current

The observed changes in the concentration of carbon, manganese, silicon, and oxygen in the weld metal as a function of distance from the start of the weld (welding time) and arc length are shown in Figs. 6–9.

As shown in Fig. 6, only small changes in carbon content were observed as a function of distance from the start of the weld. At short arc length, the carbon content increased from about 0.16 to 0.18 wt-% from a location corresponding to 1.5 in. (38.1 mm) to a location corresponding to 5.0 in. (127.0 mm) from the start of the weld. This

represents an increase of about only 10%.

On the other hand, a large increase in the manganese and silicon levels was observed as a function of distance from the start of the weld or welding time as shown in Figs. 7 and 8. The increase in manganese and silicon content was more pronounced in conditions of short and medium arc length where a higher welding current, 200 A, was used. At short arc length and 200 A, manganese and silicon increased from about 0.85 to 1.2 and from 0.07 to 0.14 wt-%, respectively, as a function of distance from the start of the weld. These changes represent an increase of about 50 and 100% of manganese and silicon, respectively.

Previous research work indicates that preheating of the SMAW electrode during welding causes a change in the size distribution of the droplets transferred across

the arc column (Ref. 15). Welding involves a considerable heating of the electrode due to the Joule effect. The higher the welding current, the higher the temperature of the electrode is as a function of weld length or welding time (Ref. 12). At the beginning of welding, the electrode is not heated as much and small size droplets predominate. As electrode preheating becomes more intense (induced mainly by the increase in resistivity with temperature of the metal core of the electrode) with increase in the weld length, globular transfer with large droplets replaces some of the small droplets (Ref. 15).

An increase in the fraction of large droplets, with a small surface area-to-volume ratio, results in an increase of recovery of manganese and silicon with welding time due to less oxidation reactions in the arc column, as shown in Figs. 7 and 8. This is confirmed by the observed decrease of oxygen along the weld deposits, as shown in Fig. 9.

Effect of Covering Moisture

The results of chemical composition analysis of the weld metal deposited with as-received and dried E8010-G electrodes are listed in Table 7. Pipe chemistry is also listed in Table 7. Minor changes in weld metal carbon content were observed with changes in the condition of the electrode. On the other hand, manganese and silicon concentrations were observed to increase significantly when dried electrodes were used. The average manganese and silicon content in the weld metals increased from about 0.97 to 1.37 wt-% and from 0.11 to 0.30 wt-%, respectively, when the condition of the electrode changed from as-received to dried. These changes represent an increase of 41 and 270% in the manganese and silicon content in the weld metal, respectively. It is clear from these data that electrode drying can have a significant impact on the weld metal manganese and silicon concentrations.

Figure 10A and B show the effect of electrode drying on droplet size and arc characteristics. Drying the electrodes had two effects. First, the droplet size increased during welding with the dried electrodes, and second, the droplet transfer rate decreased.

The observed changes in weld metal transfer behavior could be explained based on changes in arc characteristics due to the dried condition of cellulosic electrodes. Baking cellulosic electrodes leads to a reduction of gas-forming components in the covering and to the loss of hydrogen gas in the arc atmosphere, resulting in changes in the arc characteristics (Ref. 2). Different coverings ionize in the arc to different degrees. With decreasing amounts of gas evolving from the cellu-

losic covering, the percentage concentration of ionized particles of potassium, sodium, and their compounds, as well as of other easily ionized particles, is increased. Therefore, the mean ionization potential of the gaseous atmosphere of the arc is decreased because the ionization potential of the gases normally evolving from the cellulosic covering, predominantly CO, H₂O, and their dissociated products, is high and may be as much as four times higher than the ionization potential of potassium or sodium. As a result of the increased degree of ionization in the arc of dried cellulosic electrodes, the temperature of the arc decreases, the arc voltage decreases, and metal droplets become larger and larger (Ref. 13).

Another factor that may affect the droplet size and transfer rate of weld metal across the arc of dried cellulosic electrodes is the decrease in the effervescence and boiling of the melting metal electrode and covering. As indicated above, forces that result from metallurgical and gas reactions at the melting electrodes and their coverings, in particular, appear to be predominant in metal and slag transfer in the cellulosic SMAW arc. Welding with a cellulosic electrode in a dried condition, a smaller quantity of gas would evolve from the melting electrode and its covering. Therefore, partial elimination of these reactions results in less intense effervescence and/or lower frequency of forces available to assist in the metal transfer and to contribute to the fraction of weld metal that is transferred in small droplets or in spray-transfer mode.

Therefore, the increased fraction of large droplets, decreased droplet transfer rate, and lower temperature of the arc of a dried cellulosic electrode during welding may limit the kinetics and extension of oxidation reactions that may take place during disturbances of a normally reducing arc column. Additionally, the intensity and frequency of disturbances of the arc may decrease in dried cellulosic electrodes due to a decrease in effervescence and boiling. As a result, the weld metals contain more manganese and silicon due to a higher recovery of these alloying elements.

Practical Implications

The relative effect of arc length, welding current, distance from the start of the weld (weld length), and "dried" condition of the electrode on the chemical composition of the weld metal is summarized in Table 8. Arc length, weld length, and "dried" condition of the electrode have a primary effect on the chemical composition of weld metal deposited with cellulosic electrodes. Welding current has a secondary effect in the resulting chemical composition of the weld metal.

The main effect of decreasing the arc

length is to increase the carbon level in the weld metal, as indicated in Table 8, as a result of the carburizing effect of the reducing arc column atmosphere. Short arc length welding conditions result in a slight increase of manganese and silicon in the weld metal due to an increase in the recovery of these alloying elements.

As shown in Table 8, a large increase in manganese and silicon, and a decrease in oxygen in the weld metal, resulted with weld length or distance from the start of the weld. From a practical standpoint, this result suggests that higher enrichment of cellulosic weld metals could occur in normal fabrication where the use of longer beads is expected as compared to weld repair. For weld repair, short as possible weld beads are recommended to minimize weld metal composition enrichment and susceptibility to cracking. Removal and repair of defects with cellulosic electrodes often involves the combination of high restraint and high hydrogen. Therefore, if a rich weld composition can occur, it would increase the risk of cracking.

Use of cellulosic electrodes in the "dried" condition resulted in a large increase in manganese and silicon content in the weld metal, as listed in Table 8. Fabricators may store cellulosic and basic electrodes in the same oven, which causes a reduction of covering moisture. Similarly, fabricators may unknowingly leave electrodes exposed to the sun or high temperature in the field.

Therefore, extremely rich compositions could result in weld metal deposited with cellulosic electrodes due to a combination of factors including relatively rich consumables (too much addition of ferromanganese or other alloying additions, or lot-to-lot variation), which may change from manufacturer to manufacturer (Refs. 8, 19), dried electrodes, and welding with short arc length (perhaps to compensate for the decrease in arc voltage that result from welding with dried electrodes). This will affect the mechanical properties of the weld metal (Refs. 8, 19) and the susceptibility to cracking.

The effect of arc length, welding current, and location along the weld (weld length) on carbon equivalent of the weld metals is shown in Figs. 11 and 12. Consistent with the higher carbon, manganese, and silicon concentrations measured in welds made with short arc length and at locations far from the start of the weld, weld metal carbon equivalent increased with decreasing arc length and with increasing weld length. The measured carbon equivalent of the weld metals ranged from 0.26 to 0.46 wt-% due to variation of alloying (carbon, manganese, and silicon) in the weld metal induced by changes in the welding parameters and weld length. As listed in Table 7, for welds deposited using

identical lots of electrode and nearly identical welding procedures, dried cellulosic electrodes induced a change of carbon equivalent in the deposited weld metals from about 0.39 to about 0.50 wt-%.

A summary of carbon content and carbon equivalent measured in the welds that were evaluated are listed in Table 9 and plotted in Fig. 13. The base line E8010-G composition is also plotted in this figure. Figure 13 is a general graphical representation of the susceptibility to cracking of a joint as a function of carbon content and carbon equivalent (Ref. 9). In Zone I, cracking is unlikely unless high diffusible hydrogen levels or high joint restraint is present. The susceptibility to cracking increases in Zone II and Zone III requiring a better control of welding conditions, including heat input, preheat, resulting metal hardness, and hydrogen levels. The weld metal carbon and carbon equivalent changes induced by modifications in welding conditions (ΔWC) or changes in condition of the cellulosic electrodes (ΔEC) result in an increase in susceptibility of the weld metal to cracking, as indicated in Fig. 13.

Based on the experimental results, it would be a good practice to weld with coated cellulosic electrodes using as long of an arc length as practical, but within the manufacturer recommended range (too long arc length may result in high nitrogen content as shown in Fig. 3 with associated poor toughness and high risk for porosity in the weld metal), low welding current (within the recommended range), and to use the electrodes immediately after being removed from the package (as-received condition) to minimize potential enrichment of the deposited weld metals.

Proper quality assurance and training/instruction of the welder is required, as control of these variables may be difficult to carry out in the field. In welding with electrodes of a given diameter and covering thickness, the main control parameter is the magnitude of the current, while the voltage and arc length depend on the type of covering and the welder. They are not adjustable as in semiautomatic arc welding processes. Additionally, extremely dry electrodes are typically expected to not run very well and corresponding completed welds are expected to contain significant quantities of porosity. However, electrode formulations have evolved through the years to improve operator appeal, and it is possible that specific formulations have improved to the point where acceptable operation continues even with a dry covering. During the deposition of the experimental welds, no drastic change in performance was observed when using the dried E8010-G electrode. Additionally, welds deposited using electrodes in the dried condition were subjected to X-ray inspection to ver-

ify weld soundness, and no substantial increase in weld porosity was observed in the E8010-G deposits either. Therefore, it may be difficult in the field to determine the condition of the electrodes based on their performance during welding.

Conclusions

Based on the experimental observations and discussions, the following conclusions are presented:

- Factors other than lot-to-lot variation in electrode composition are primarily responsible for rich compositions measured in the specific evaluated welds that experienced hydrogen-assisted cracking.

- Arc length, weld length (welding time), and “dried” condition of the electrode have a primary effect on the chemical composition of weld metal deposited with cellulosic electrodes. Welding current has a secondary effect in the resulting chemical composition of the weld metal.

- The main effect of decreasing the arc length was a 100% increase in carbon level in the experimental weld metals, from about 0.08 to about 0.16 wt-%. The weld metal nitrogen content decreased from about 700 to 100 ppm, and the manganese content in the weld metal changed from about 0.7 to 0.9 wt-%, about a 25% increment, as the arc length was decreased.

- A large increase in manganese and silicon, and decrease in oxygen in the weld metal resulted with weld length or distance from the start of the weld, especially at high welding currents. At short arc length and 200 A, manganese and silicon increased from about 0.85 to 1.2 (about 50%), and from 0.07 to 0.14 (about 100%) wt-%, respectively, as a function of the distance from the start of the weld. Only small changes, about 10%, of carbon content were observed as a function of distance from the start of the weld.

- Use of cellulosic electrodes in “dried” conditions has a significant impact on the weld metal manganese and silicon concentrations. Average manganese and silicon content in the weld metals increased from about 0.97 to 1.37 wt-%

(41% increase) and from 0.11 to 0.30 wt-% (270% increase), respectively, when the condition of the electrode changed from as-received to dried. Only minor changes in weld metal carbon content were observed with a change in the condition of the electrode. The weld metal transfer along the arc column of a “dried” cellulosic electrode was characterized by an increased fraction of larger droplets and decreased droplet transfer rate as compared to that of an as-received electrode.

- The alloying enrichment of weld metals, as represented by changes in carbon and carbon equivalent (CE), induced by modifications in welding conditions (Δ WC; CE ranges from 0.26 to 0.46) or changes in condition of the cellulosic electrodes (Δ EC; CE ranges from 0.39 to 0.50) or by a combined effect result in an increase in susceptibility of the weld metal to hydrogen assisted cracking.

- During welding with coated cellulosic electrodes, it would be a good practice to avoid too short arc length, use low welding current as practical and within the range recommended by the manufacturer, and to use the electrodes immediately after being removed from the package (as-received condition) to minimize potential enrichment of deposited weld metals. Proper quality assurance and training/instruction of welders is recommended as well.

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