Examining the Mechanical Properties of High-Strength Steel Weld Metals

Tensile, Charpy impact toughness, and crack-tip opening displacement toughness of high-strength steel weld metals were characterized

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Fig. 1 — General view of the welded joint.

The major impetus for developments in high-strength steels (HSS) has been provided by the need for higher strength, increased toughness, and improved weldability (Ref. 1). High-strength steels with yield strengths of 450 MPa (X70) and 550 MPa (X80) are increasingly specified for use in different structural applications resulting in weight and cost savings through the use of thinner sections (Refs. 2, 3). Additional refinement of chemical composition and processing procedures have resulted in the development and testing of higher-strength steels, X100 and X120 (Refs. 4, 5). As a result, new developments in welding processes and consumables to produce weld metal deposits with mechanical properties essentially equivalent to the base metal are continually needed. To achieve this, however, proper understanding of chemistry- and microstructure-property relationships in HSS weld metals is required.

Characterization of High-Strength Steel Weld Metal

High-strength steel weld metals were deposited using different welding processes and commercially available consumables. Welds were produced using flux-shielded processes such as flux cored arc welding (FCAW) and shielded metal arc welding (SMAW) and gas-shielded processes such as gas metal arc welding (GMAW). Flux cored arc welding included both self- (T-8 type) and gas-shielded electrodes. Cellulosic and basic electrodes were used with the SMAW process. The nominal strength of the welding consumables ranged from 490 to 840 MPa (70 to 120 ksi). Table 1 provides a summary of the consumables, welding processes, and weld identifications (W1 to W14) used in this study. Welding parameters are summarized in Table 2. Figure 1 shows a general view of a welded joint prepared for weld metal characterization.

The mechanical characterization of the HSS weld metals deposited included tensile properties, Charpy impact properties,

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Table 1 — Summary of Base Metals, Welding Processes, Welding Consumables, and Identifications of Different Weld Metals Characterized in this Program

Welded Joint	Base Metal	Welding Process	Welding Condition	Filler Metal	Procedure/Shielding Gas
W1	Plate, SA-36	FCAW	Semiautomatic	E71T-1(a)	CO_2
W2	Plate, SA-36	FCAW	Semiautomatic	E71T-1	CO_2
W3	Unknown	GMAW	Semiautomatic	ER70S-7(b)	CO_2
W4	Unknown	GMAW	Semiautomatic	ER70S-6(c)	CO_2
W5	Pipe, X80	SMAW	Manual	E8010-G	NA
W6	Pipe, X80	SMAW	Manual	E9010-G	NA
W7	Pipe, X80	SMAW	Manual	E9018-G	NA
W8	Pipe, X80	FCAW-S	Semiautomatic	E91T8-G	NA
W9	Plate, X100	GMAW	Automatic	ER100S-1(b)	Internal/external $100CO_2$
W10	Plate, X100	GMAW	Automatic	ER100S-1(c)	Internal/external, pulsed, $85Ar\text{-}15CO_2$
W11	Plate, X100	GMAW	Automatic	ER100S-1(c)	Internal/external, dual torch, pulsed, $85Ar\text{-}15CO_2$
W12	Plate, X100	GMAW	Automatic	ER100S-1(b)	External, pulsed, $95\ Ar\text{-}5CO_2$
W13	Plate, X100	GMAW	Automatic	ER120S-1	Internal-external $100CO_2$
W14	Plate, X100	GMAW	Automatic	ER120S-1	Internal/external, pulsed, $85Ar\text{-}15CO_2$

(a) Microalloyed; (b) and (c) represent different consumable manufacturers.

Table 2 — General Welding Conditions Used to Deposit Weld Metals W1 to W14

Welded Joint	Welding consumable		Preheat/Interpass Temperature, °C	Nominal Heat Input, kJ/mm
	Root Pass	Fill Pass		
W1	E71T-1(a)	E71T-1(a)	RT/150	1.8 to 2.0
W2	E71T-1	E71T-1	RT/150	1.8 to 2.0
W3	ER70S-7	ER70S-7	Unknown	Unknown
W4	ER70S-6	ER70S-6	Unknown	Unknown
W5	E8010-G	E8010-G	RT/120	1.3
W6	E9010-G	E9010-G	RT/120	1.5
W7	ER70S-6, STT(b)	E9018-G	RT/120	1.3
W8A(c)	ER70S-6, STT(b)	E91T8-G	RT/110	0.9
W8B(d)	ER70S-6, STT(b)	E91T8-G	RT/120	1.2
W8C(e)	ER70S-6, STT(b)	E91T8-G	RT/52	1.1
W8D(f)	ER70S-6, STT(b)	E91T8-G	RT/290	1.0
W9	ER100S-1	ER100S-1	50/150	0.76
W10	ER100S-1	ER100S-1	50/150	0.80
W11	ER100S-1	ER100S-1	50/150	0.9
W12	ER100S-1	ER100S-1	50/150	0.82
W13	ER120S-1	ER120S-1	50/150	0.77
W14	ER120S-1	ER120S-1	50/150	0.85

(a) Microalloyed; (b) Surface Tension Transfer®; (c) welder A; (d) welder B; (e) low interpass temperature (cold); (f) high interpass temperature (hot).

and fracture toughness using crack-tip opening displacement (CTOD). All-weld-metal tensile properties were measured by using round ASTM E8 tensile specimens. Full-size Charpy V-notch (CVN) specimens were machined transverse to the weld length and notched through-thickness in the weld metal. Weld metal CTOD tests were conducted at –10°C following procedures given in ASTM E1290-93. The CTOD weld samples were machined B × 2B in size and transverse to the weld length with the notch oriented in the through-thickness direction at the weld centerline. One hundred sixty-six CTOD tests representing the 14 weld metals were conducted.

In order to assess the variability in weld metal properties, in some of the welds, specimens for Charpy impact testing and CTOD testing were machined with the notch or crack off the weld centerline. Additionally, specimens from some pipe welds were obtained from different locations corresponding to the 12, 3, and 6 o'clock positions. The effect of the welder on mechanical properties was considered as well.

Table 3 — Selected Chemical and Nonmetallic Inclusion Characteristics of Deposited Weld Metals (Ref. 6)

Welded Joint	Carbon Equivalent CE_{IIW}	Pcm	Oxygen Content (ppm)	Average Inclusion Diameter (um)	Carbon Content (%)	Nitrogen Content (ppm)
W1	0.326	0.177	520	0.532	0.054	73
W2	0.257	0.131	—	0.517	0.021	—
W3	0.353	0.172	460	0.391	0.066	30
W4	0.319	0.157	460	0.320	0.056	80
W5	0.268	0.151	650	0.491	0.100	210
W6	0.310	0.220	500	0.354	0.154	110
W7	0.390	0.156	460	0.311	0.060	120
W8A	0.482	0.203	110	—	0.071	370
W8C	0.537	0.228	110	0.314	0.084	323
W8D	0.509	0.215	110	—	0.074	323
W9	0.496	0.204	560	0.401	0.068	70
W10	0.485	0.202	310	0.298	0.061	80
W11	0.471	0.197	360	0.326	0.068	140
W12	0.054	0.208	260	0.367	0.055	40
W13	0.651	0.289	450	—	0.110	60
W14	0.726	0.302	280	0.299	0.100	90

Table 4 — All-Weld-Metal Tensile Properties

Welded Joint	Filler Metal	Ultimate Tensile Strength (UTS) (MPa)	(ksi)	0.2% Yield Strength (MPa)	(ksi)	Elongation (%)	Reduction of Area (%)
W1	E71T-1-M	588	85	514	75	25.4	65.5
W2	E71T-1	518	75	443	64	28.8	76.3
W3	ER70S-7	703	102	644	93	27.0	70.0
W4	ER70S-6	699	101	634	92	28.0	66.0
W5	E8010-G	609	88	539	78	23.2	56.0
W6	E9010-G	655	95	569	82	24.2	60.9
W7	E9018-G	657	95	586	85	26.2	69.1
W8A	E91T8-G	734	106	683	99	16.6	38.9
W8C	E91T8-G	754	109	667	96	16.3	29.5
W8D	E91T8-G	740	107	609	88	23.2	56.0
W9	ER100S-1	794	115	752	109	13.0	71.0
W10	ER100S-1	814	118	752	109	12.0	43.0
W11	ER100S-1	768	111	719	104	15.0	75.0
W12	ER100S-1	792	115	768	111	18.0	52.0
W13	ER120S-1	NA	NA	NA	NA	NA	NA
W14	ER120S-1	1111	161	1028	149	3.0	22.0

Observed Characteristics of HSS Weld Metals

Alloying, Microstructure, and Tensile Properties Relationships. As discussed in a previous publication (Ref. 6), the chemical composition of the deposited HSS weld metals was based on a C-Mn system with additions of deoxidizers (silicon, manganese, aluminum, titanium) and additions of various alloying elements (nickel, chromium, molybdenum, boron, niobium, vanadium, and copper). The effect of alloying levels on the hardenability of the weld metal is reflected in the carbon equivalent number (CE_{IIW}). The CE_{IIW} carbon equivalent of weld metals deposited with E70X-E80X, E90X, and E100X-E120X grade consumables range from 0.25 to 0.35, 0.31 to 0.54, and 0.47 to 0.73, respectively, as listed in Table 3.

Additionally, as reported previously (Ref. 6), two major trends were observed in the change of microstructure of the deposited weld metals as the CE_{IIW} carbon equivalent increased. The fraction of low-temperature products increased and the microstructure became finer as the carbon equivalent increased. The weld metals with a carbon equivalent between 0.26 (W2) and 0.39 (W7) consisted mainly of a ferritic microstructure with a decreasing fraction of grain boundary ferrite and an increasing fraction of lower-temperature transformation products such as side-plate ferrite and acicular ferrite. In weld metals with a carbon equivalent of 0.47 or higher (W8 to W14), an increasing fraction of lower transformation products, including martensite, was present.

The tensile properties of Welds W1 through W14 are listed in Table 4. A yield strength as high as 1030 MPa (150 ksi) was obtained in the weld metal deposited with the E120X consumable and the pulsed gas metal arc welding (GMAW-P) process (W14). As shown in Fig. 2, the weld metal strength increases with an increase in the CE_{IIW} carbon-equivalent number. In the yield strength range between 65 and 150 ksi, a good correlation was observed between the strength of the weld metal and the CE_{IIW} carbon-equivalent number of the weld deposits.

These observations indicate that, although the carbon equivalents were originally developed with the view of evaluating the base metal cold cracking susceptibility, these general empirical equations can also be useful in understanding the

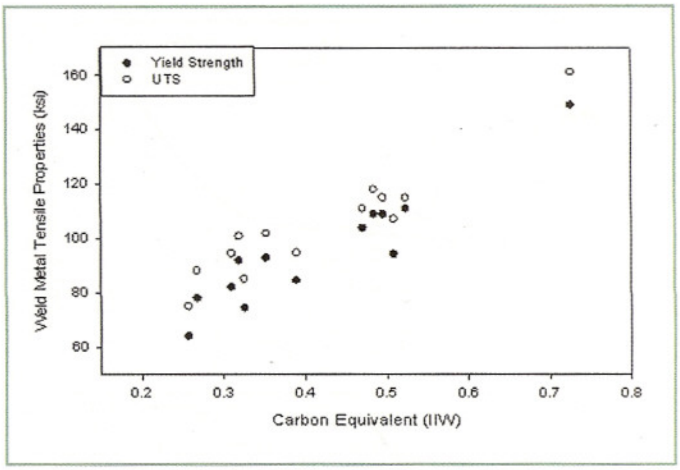


Fig. 2 — Weld metal yield and tensile strength as a function of the CE_{IIW} carbon equivalent number.

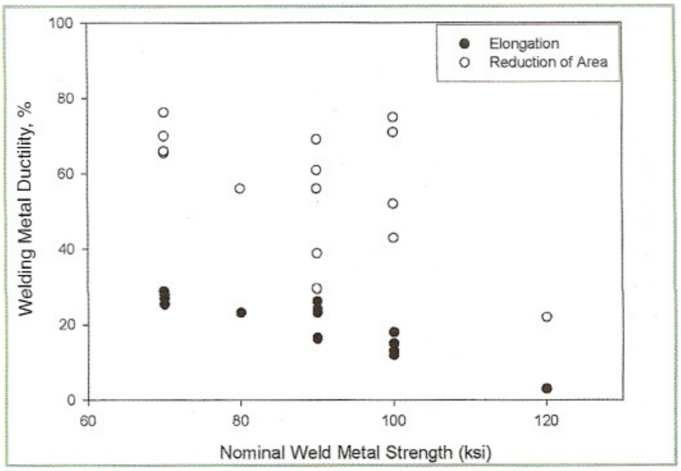


Fig. 3 — Ductility of the weld metal, percent elongation, and reduction in area as a function of the nominal strength of the consumables.

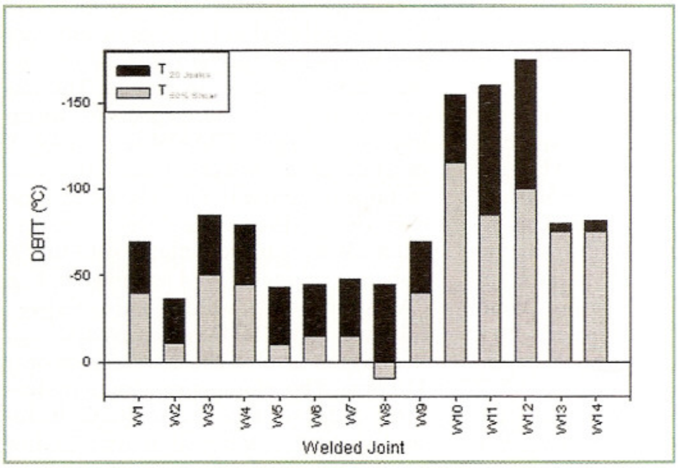


Fig. 4 — Ductile-to-brittle transition temperatures of the weld metals determined based on the 20 J and the 50% shear area criteria.

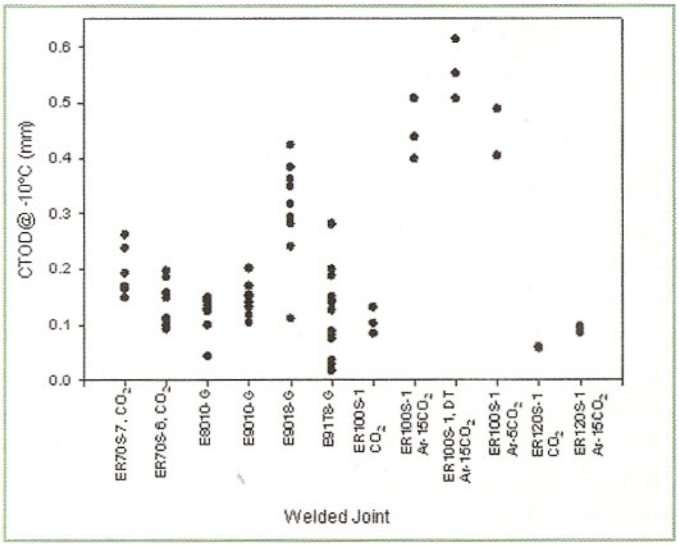


Fig. 5 — CTOD toughness of weld metals at –10°C.

complex relationship between the high-strength steel weld metal hardenability as controlled by the alloying content, the resulting microstructural transformation behavior of the weld deposit, and associated tensile properties.

Figure 3 shows the ductility of the weld metals in terms of elongation and reduction of area, as a function of the nominal strength of the welding consumable. As expected, the ductility of the weld metal decreases as the strength increases. Elongations as low as 13 and 3% were observed in weld metal deposited with E100X and E120X consumables, respectively. Therefore, the challenge in welding HSS is to provide high-strength weld metals with adequate ductility and toughness.

Impact Fracture Toughness. Weld metals W1 to W14 exhibit different impact Charpy behavior as described by the ductile-to-brittle transition curves. Figure 4 shows the ductile-to-brittle transition temperatures (DBTT) of the deposited weld metals as determined by the 20 J and 50% shear area criteria. The DBTT 20 J of the deposited weld metals ranged from –35° to –170°C.

For practical reasons, it is important to indicate that taking into account the fracture behavior of the different deposited weld metals as described by the different shapes of the ductile-to-brittle transition curves, the use of different criteria such as absorbed energy at a specific temperature (Refs. 7, 8) may indicate different relative performances of the weld metals.

CTOD Fracture Toughness. The results of the CTOD testing at –10°C of the different weld metals are shown in Fig. 5. In general, the CTOD toughness of the weld metals at –10°C shows a lot of scattering. The CTOD of the tested welds at –10°C ranges from about 0.01 to 0.62 mm. Cracking tip opening displacement toughness greater than 0.25 mm at –10°C is normally required for offshore structure applications. As observed in Fig. 5, most of the weld metal deposited did not meet this requirement. Therefore, as pointed out earlier, the greatest challenge in welding HSS is to provide high-strength weld metals with adequate ductility and toughness.

It was observed that weld metals with similar microstructures and yield strengths showed very different CTOD properties. For example, weld metal W7 showed a high maximum value of CTOD (0.45 mm) as compared to other welds with similar yield strength like weld metal W6, which showed a maximum value of CTOD equal to 0.2 mm. A similar but more pronounced difference was observed between the CTOD results of weld metal W9 and weld metals W10, W11, and W12. All these welds were made using the same welding wire type but different GMAW process modes and associated

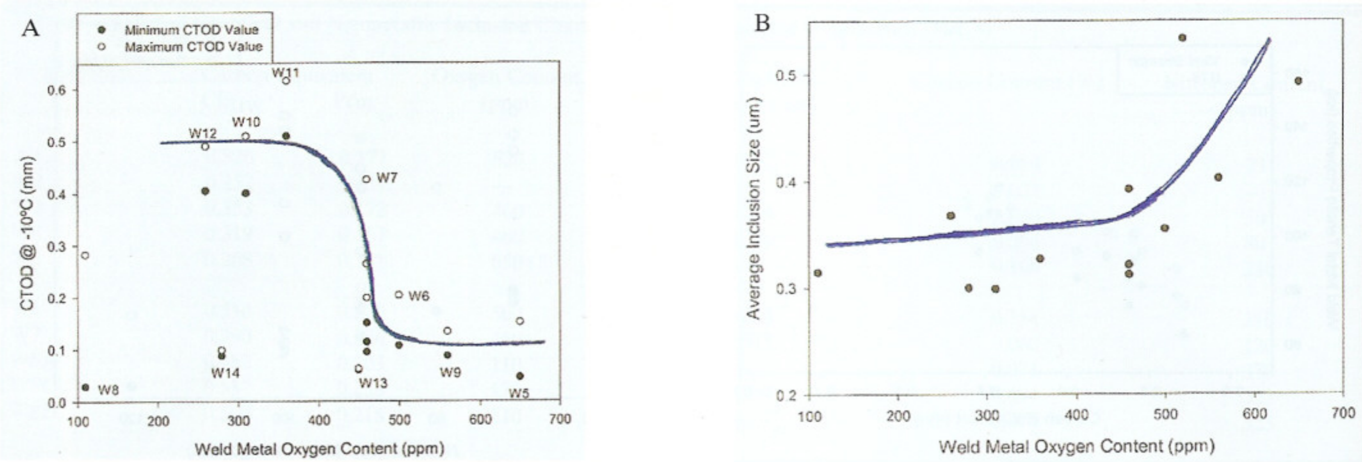


Fig. 6 — A — Weld metal CTOD as a function of weld metal oxygen content; B — average inclusion size as a function of weld metal oxygen content.

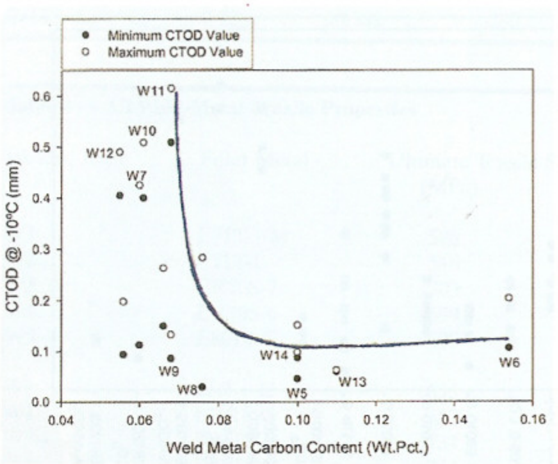


Fig. 7 — Weld metal CTOD as a function of carbon content in the weld metal.

shielding gases as listed in Tables 1 and 2. However, even though the primary microstructures of these welds were not very different (Ref. 6) and the yield strengths of all four welds were similar, ranging from 104 to 111 ksi, there was an increase in CTOD values between 4 and 6 times in welds W10, W11, and W12 (CTOD between 0.4 and 0.6 mm) as compared to the CTOD value of weld metal W9 (CTOD value of 0.1 mm).

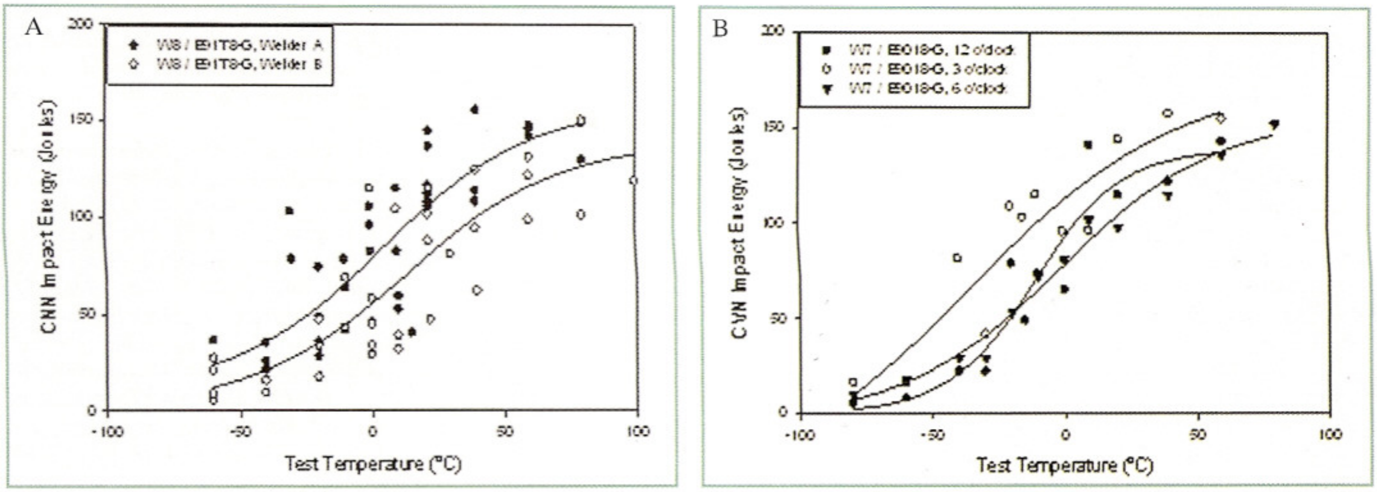
Figure 6A shows the relationship between weld metal CTOD and the oxygen content in the weld metal. There is a good trend between weld metal CTOD and the oxygen content in the weld metal. This trend may be broken down into three distinct regions. An upper-shelf CTOD region in weld metals with oxygen content below about 360 ppm, a transition CTOD region that corresponds to weld metal oxygen content between 360 and 500 ppm, and a lower-shelf CTOD region in weld metals with oxygen content of 500 ppm or higher. This observed trend helps to explain the difference in CTOD behavior observed in weld metals with similar yield strength and microstructure as described in the previous paragraph.

The oxygen content in weld metal W6 ($CTOD_{max}$ value of 0.20 mm) and W7 ($CTOD_{max}$ value of 0.45 mm) was 500 and 460 ppm, respectively. This indicates a transition from the lower-shelf CTOD to the transition CTOD region. Weld metal W6 was deposited with a SMAW cellulosic electrode (E9010-G) and weld metal W7 was deposited with a SMAW basic electrode (E9018-G). For weld metals W9 to W12, the increase in CTOD from about 0.1 mm in W9 to a CTOD value between 0.4 and 0.6 mm in welds W10 to W12 resulted from a decrease in oxygen content in the weld metal from 560 ppm in W9 to an oxygen content in the range of 260 to 360 ppm in welds W10 to W12. This corresponds to a transition from the lower-shelf CTOD region to the upper-shelf CTOD region. The lower oxygen level in weld metals W10 to W12 resulted from the GMAW-P process used with Ar (5–15)/CO_2 shielding gas as compared to the normal GMAW process with 100% CO_2 shielding gas for weld metal W9.

Figure 6B shows the average nonmetallic inclusion size as a function of the oxygen content in the weld metals (Ref. 6). The average inclusion size does not change drastically for oxygen contents of up to about 450 ppm. However, a pronounced increase in the average inclusion size occurred as the oxygen content in the weld metal increased from about 460 ppm. This indicates that the distribution size of inclusions in the weld metal change toward a larger inclusion size for oxygen contents larger than 460 ppm. The increase in average inclusion size increases the possibility that large inclusions can provide a crack nucleus for cleavage fracture initiation in weld metals. The improvement of CTOD toughness by switching from normal GMAW to GMAW-P procedures was not observed in the weld metal deposited with an E120X electrode even though the oxygen level decreased from 450 ppm in weld metal W13 to 280 ppm in weld metal W14 as shown in Fig. 6A. Additionally, weld W8 also showed relatively low CTOD values even though the oxygen level in these welds was only 110 ppm. Therefore, microstructural features different from nonmetallic inclusions may be responsible for the low CTOD values observed in weld metals W14 and W8.

Figure 7 shows the weld metal CTOD values as a function of carbon content in the weld metals. Carbon levels of about 0.08 wt-% or higher in the weld metal resulted in low CTOD values. This behavior may result from the presence of carbides that precipitate due to the high level of carbon present in these weld metals. Therefore, the high carbon levels and resulting precipitation of carbides may be responsible for the low CTOD values observed in weld metal W14 even at low oxygen levels. Evaluation of the origin of microcracks in high-purity iron indicated that almost every microcrack found was associated with the fracture of a carbide particle even at carbon levels below the solubility limits (Ref. 9). Therefore, carbides provide effective nucleation sites for crack initiation.

In the case of weld metal W8, the oxygen and carbon levels were 110 ppm and 0.076%, respectively, as listed in Table 4. Those levels correspond to the upper-shelf CTOD region based on oxygen content and below the critical carbon level of 0.08% identified in Fig. 7 and, therefore, do not explain the relatively low CTOD



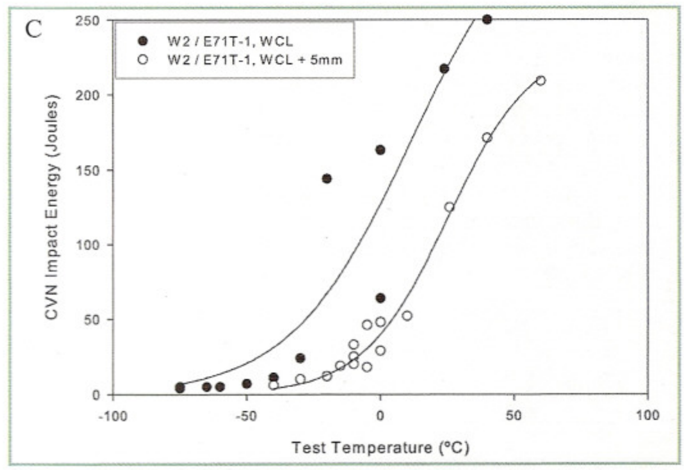


Fig. 8 — Charpy V-notch transition curves of the following: A — Weld metals deposited by two different welders; B — as a function of the sample locations; C — as a function of notch location relative to the weld centerline.

values observed in W8 weld metal as shown in Fig. 6A. However, the nitrogen level in this weld metal was about 330 ppm, which was the highest nitrogen level measure in any of the evaluated weld metals. Weld metal W8 was deposited with FCAW using a self-shielding electrode (T-8 type). This type of consumable is very susceptible to nitrogen pickup from the environment and a high level of aluminum is normally used in the design of the consumable to tie up the nitrogen in the weld metal. Therefore, dissolved nitrogen and/or nitrides instead of nonmetallic inclusion or carbides may be responsible for the relatively low CTOD observed in weld metal W8.

The observed CTOD behavior of the deposited weld metals confirms that the toughness behavior of multipass weld metal is complex and the event controlling the fracture behavior changes from system to system. Minor phases including martensite-austenite-carbide (MAC) complexes, nonmetallic inclusions, and carbides or nitrides are also present in weld metals. These minor phases may act as local brittle zones (LBZs). The morphology and distribution of LBZs have a strong influence on the toughness of the weld metal. Therefore, in order to evaluate and understand the CTOD fracture toughness behavior of high-strength weld metals, it is important to conduct fractographic analysis of the crack initiation sites and of the associated microstructural features.

The experimental observation also indicates that the welding processes used to join HSS greatly influence the CTOD properties of the resultant weld metals. Generally, the best weld CTOD metal properties are achieved with the gas-shielded processes. Gas-shielded weld metals usually contain lower amounts of oxygen and nitrogen than their flux-shielded metal arc counterparts (Ref. 6). Table 3 lists the levels of oxygen and nitrogen observed in the weld metals deposited with different welding processes and consumables. In general, a consumable/process could be classified as low, medium, or high nitrogen if the amount of nitrogen in the metal weld deposit is less than 70 ppm, between 70 and 120 ppm, and greater than 120 ppm, respectively (Refs. 10, 11).

Variability of Mechanical Properties. It has been reported that high-strength weld metals exhibit a high degree of variability in mechanical property test results (Refs. 12, 13). The variability of the properties of a weld metal could come from various sources such as consumable lot-to-lot variation, procedural variation, positional variation, and base material variation. In this study, it was observed that variability of Charpy impact properties of weld metals deposited with a given welding consumable and welding process may be dependent on the welder, location of the samples relative to the general layout of a pipe weld, and on the location of the notch relative to the centerline of the weld, as illustrated in Figs. 8A, B, and C, respectively.

As observed in impact fracture toughness, the results of CTOD toughness of some tested weld metals showed also variation that is dependent on the welder and location of the samples relative to the general configuration of the welded joint. Another potential source of scatter in the measurement of CTOD fracture toughness is the proportion of low toughness microstructure present at the crack tip. Experimental evidence indicates that the length of the low toughness microstructure along the crack front can influence the test results. Experimental work has indicated that lower bound fracture toughness values were obtained when more than about 15 to 20% low toughness microstructure was present along the crack front (Ref. 14).

Conclusions

The deposited HSS weld metals showed the following characteristics:

- The CE_{IIW} carbon equivalent provides a good correlation between the chemical composition, microstructure, and resulting tensile properties of the evaluated weld metals.
- The yield strength ranges between 65 and 150 ksi. A weld metal with yield strength as high as 1030 MPa (150 ksi) was obtained with E120X consumables.
- The ductility, elongation, and reduction of area of the weld metal decreases as the strength increases. Elongations as low as 13% and 3% were observed in weld metal deposited with E100X and

E120X consumables, respectively.

- The weld metals exhibit different impact Charpy behavior. The DBTT 20 J of the deposited weld metals range from –35 to –170°C.
- The CTOD toughness of the weld metals at –10°C shows a lot of scattering and ranges from 0.01 to 0.62 mm. Weld metal yield strength does not have a clear effect on CTOD toughness. Oxygen, carbon, and nitrogen levels in the weld metal greatly affect the CTOD toughness of the weld metal.
- The best CTOD toughness was observed in weld metals with oxygen, carbon, and nitrogen levels ranging from 260 to 360 ppm, 0.055 to 0.068%, and 40 to 140 ppm, respectively. Generally, the best weld CTOD properties were achieved with gas-shielded processes.
- Variability of Charpy impact and CTOD toughness of weld metals deposited with a given welding consumable and welding process was associated with welder, location of the test samples relative to the general layout of the weld, and to the location of the notch in the test sample relative to the centerline of the weld.◆

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