SMAW, FCAW, and SAW High-Strength Ferritic Deposits: The Challenge Is Tensile Properties

Consistently satisfying the minimum requirements for tensile strength demanded a rigorous approach to welding parameter selection in order to obtain repeatable results

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ABSTRACT

The objective of this work was to analyze the influence of chemical composition and welding parameters on microstructure and mechanical properties of medium- and high-strength steel all weld metals of both C-Mn-Ni-Mo and C-Mn-Ni-Mo-Cr ferritic types produced with coated electrodes, flux cored arc welding electrodes, and wire/flux combinations for submerged arc welding and compare these results with AWS requirements. Chemical composition of the deposits was varied and welding parameters were changed in the production of all-weld-metal samples according to the relevant AWS standards of the consumables employed. Tensile properties, hardness, and Charpy-V impact toughness of the all-weld-metal specimens were assessed and metallographic studies were conducted with light microscopy in order to correlate mechanical properties with resulting microstructures. From the analysis of the results it was concluded that achieving the toughness required by the standards was not a problem. On the contrary, consistently satisfying the minimum requirements for tensile strength turned out to be much more difficult, demanding a rigorous approach to welding parameter selection in order to obtain repeatable results. On the other hand, for a given type of weld deposit, the requirements to be met differ according to the welding process employed, thus adding another variable to the difficulties in satisfying the tensile requirements of the different standards.

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Introduction

It is well known that when selecting a C-Mn steel as an alloy base, in order to increase tensile strength it becomes necessary to add to the alloy base alloying elements such as Ni, Mo, and/or Cr, which will modify other properties as well (Refs. 1, 2). It is also known that an increase in tensile strength is frequently accompanied by a loss in toughness, particularly at low temperatures (Refs. 3, 4). For this reason, when designing an electrode formulation starting with C-Mn consumables, the main concern is devoted to maintaining the toughness requirement and the achievement of adequate tensile properties is seldom of concern.

The AWS standards that currently classify the welding consumables for C-Mn-Ni-Mo and C-Mn-Ni-Mo-Cr medium- and high-strength alloy steels are AWS A5.5/A5.5M:2006 (Ref. 5) for shielded metal arc electrodes (SMAW), ANSI/AWS A5.29/A5.29M:2005 (Ref. 6) for flux cored arc welding electrodes (FCAW), and AWS A5.23/A5.23M:2007 (Ref. 7) for flux/wire combinations for submerged arc welding (SAW). According to these standards, all weld metal must meet chemical composition, tensile properties, and Charpy V-notch impact test requirements, among others.

KEYWORDS

High-Strength Steels
Tensile Properties
Weld Metal Impact Toughness
Weld Metal Hardness
Weld Deposit Microstructures
SMAW
FCAW
SAW

Tables 1 and 2 present the all-weld-metal chemical composition and mechanical properties requirements for the consumables employed in this work. It can be observed that there are several types of consumables corresponding to different welding processes that exhibit approximately similar properties, which would suggest the same type of application. Nevertheless, while, for example, manual electrodes of the E11018M type (Ref. 5) require 760 MPa of minimum tensile strength and yield strength in the range 680–760 MPa, for the equivalent tubular electrode E111T5-K3 (Ref. 6), there is a single minimum yield strength requirement of 680 MPa and an extended tensile strength range of 760–900 MPa. The minimum elongation requirement is also different for both consumables: 20% for the manual electrode and 15% for the tubular electrode. On the other hand, the toughness requirements are the same for all these consumables: a mean value of 27 J at –51°C (–60°F) with 20 J minimum for each individual value. It is important to take into account that for SMAW consumables the specifications are military ones, then with special requirements; it is not so for the rest of the welding consumables used.

The general objective of this work was to analyze and compare mechanical properties measured at different stages of the study program on the performance of high-strength ferritic all-weld metals conducted by the authors. The specific objective was to analyze the influence of chemical composition and welding parameters on microstructure and mechanical prop-

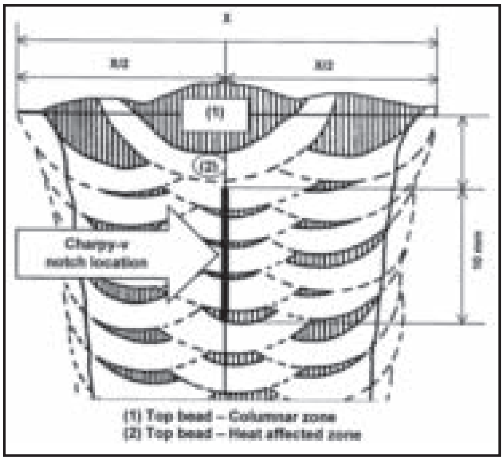

Fig. 1 — Charpy V-notch location.

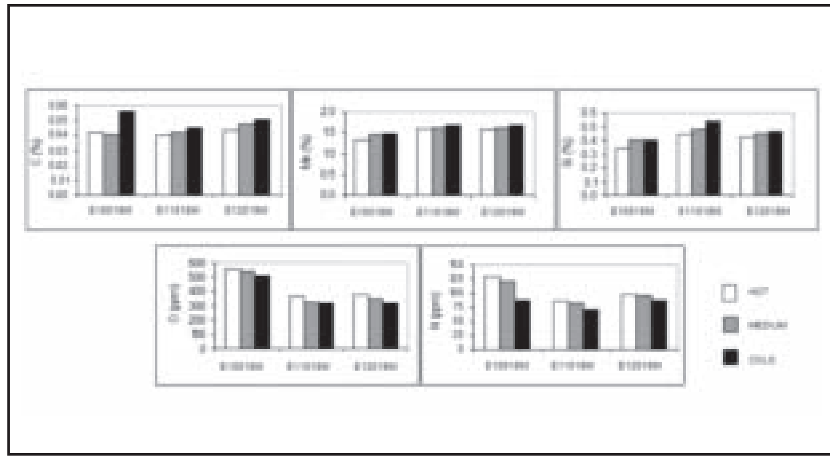

Fig. 2 — Heat input influence on all-weld-metal chemical composition (SMAW).

Table 1 — All-Weld-Metal Chemical Requirements According to the Corresponding AWS Standards: SMAW, A5.5-81 and A5.5-96; FCAW, A5.29-98 and A5.29/29M:2005; SAW, A5.23-97

Process	Classification	C	Mn	P	S	Si	Ni	Cr	Mo
SMAW	E10018M	0.10	0.75–1.70	0.030	0.030	0.60	1.40–2.10	0.35	0.25–0.50
SMAW	E11018M	0.10	1.30–1.80	0.030	0.030	0.60	1.25–2.50	0.40	0.25–0.50
SMAW	E12018M	0.10	1.30–2.25	0.030	0.030	0.60	1.75–2.50	0.30–1.50	0.30–0.55
FCAW	E91T5-K2 E101T5-K3	0.15	0.50–1.75	0.03	0.03	0.80	1.25–2.60	0.15	0.35
FCAW	E111T5-K3	0.15	0.75–2.25	0.03	0.03	0.80	1.25–2.60	0.15	0.25–0.65
FCAW	E120T5-K4	0.15	1.20–2.25	0.03	0.03	0.80	1.75–2.60	0.20–0.60	0.20–0.65
SAW	F9/10/11/12 A6-ECM2-M2	0.10	0.90–1.80	0.030	0.040	0.80	1.40–2.10	0.35	0.25–0.65

Single values are maximums.

Table 2 — All-Weld-Metal Mechanical Property Requirements According to the Corresponding AWS Standards: SMAW, A5.5-81 and A5.5-96; FCAW, A5.29-98 and A5.29/29M:2005; SAW, A5.23-97

Process	Classification	TS (MPa)	YS (MPa)	E (%)	Ch-V at – 51°C
SMAW	E10018M	690	610–690	20	27
SMAW	E11018M	760	680–760	20	27
SMAW	E12018M	830	745–830	18	27
FCAW	E91T5-K2	620–760	540	17	27
FCAW	E101T5-K3	690–830	610	16	27
FCAW	E111T5-K3	760–900	680	15	27
FCAW	E120T5-K4	830–970	750	14	27
SAW	F9A6-ECM2-M2	620–760	540	17	27
SAW	F10A6-ECM2-M2	690–830	610	16	27
SAW	F11A6-ECM2-M2	760–900	680	15*	27
SAW	F12A6-ECM2-M2	830–970	750	14*	27

Single values are minimums.
* Elongation may be reduced by one percentage point for both classifications weld metals in the upper 25% of their tensile strength range.

erties of medium- and high-strength steel all-weld metals. The weld deposits were of the C-Mn-Ni-Mo and C-Mn-Ni-Mo-Cr ferritic types produced with different welding consumables. These consumables were coated electrodes, flux cored arc welding electrodes, and wire/flux combinations for submerged arc welding. The purpose behind this selection was to identify the difficulties to satisfy all-weld-metal mechanical property requirements of the respective AWS standards since, contrary to common perception, achieving the required level of all-weld-metal tensile strength is in general more difficult than impact properties due to the limitations imposed by the standard requirements on yield strength and to some extent, by the required welding procedure variables.

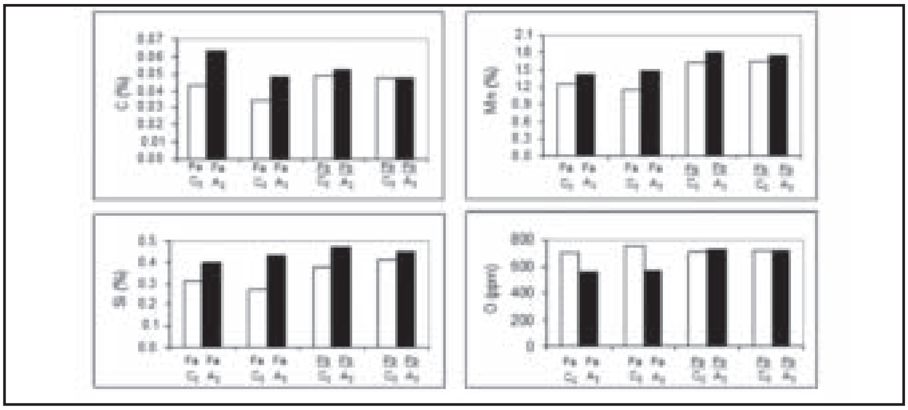

Fig. 3 — Gas shielding type influence on all-weld-metal chemical composition (FCAW).

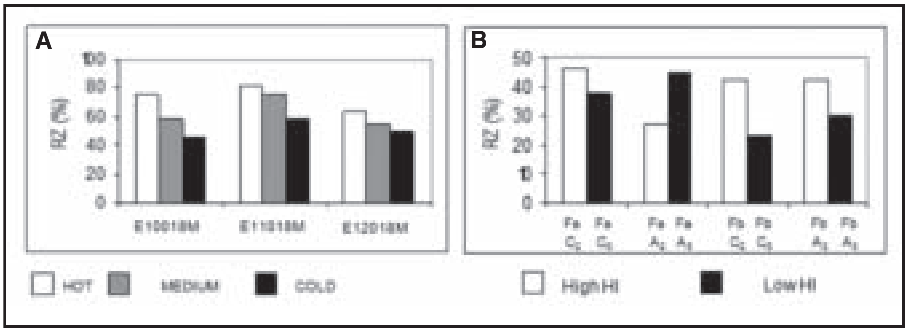

Fig. 4 — Heat input influence on reheated zone: A — SMAW; B — FCAW.

Experimental Procedure

Consumables

The welding consumables employed were SMAW electrodes of the ANSI/AWS A5.5-81 (Ref. 8) E10018M, E11018M, and E12018M commercial type; FCAW electrodes of the ANSI/AWS A5.29-98 (Ref. 9) E91T5-K2/E101T5-K3, E111T5-K3, and E120T5-K4 commercial types; and SAW flux/wire experimental combinations of the ANSI/AWS A5.23-97 (Ref. 10) F9/F10/F11 and F12A6-ECM2-M2 types, with a basic flux of BI = 2.5, Boniszewski basicity index (Ref. 11), for all cases. All-weld-metal test coupons in the flat welding position, varying the welding procedure but always within the requirements of the corresponding standards were produced with all the consumables studied.

For the analysis, results from submerged arc weldments specifically produced for this work were used together with those generated by the authors in previous research on SMAW (Refs. 12, 13) and FCAW (Refs. 14–16) processes.

Weldments

SMAW. With each one of the mentioned consumables, three all-weld-metal test pieces were produced (cold: 1.2–1.5 kJ/mm, medium: 1.6–2.0 kJ/mm, hot: 2.0–2.2 kJ/mm) varying the welding parameters according to Table 3 within the allowable range of the corresponding standard. The specimens were identified as E10018M c (cold), m (medium), h (hot); E11018M c (cold), m (medium), h (hot); and E12018M c (cold), m (medium), h (hot).

FCAW. All-weld-metal test pieces were produced with four FCAW wires varying the shielding gas composition (CO_2 and Ar 80%/CO_2 20%) and the number of passes per layer (2 or 3). Identification: with flux cored wire "Fa," samples FaC2, FaC3, FaA2, and FaA3, with flux cored wire "Fb," samples FbC2, FbC3, FbA2, and FbA3, with flux cored wire F1, samples F1C3 and F1C2, and with flux cored wire F2, only sample F2C3; C meaning CO_2 shielding and A corresponding to 80%Ar/20%CO_2 mixture shielding and the numbers following C or A, depict the number of passes per layer (Table 3).

SAW. Eight all-weld-metal samples were produced employing four 3.2-mm-diameter wires of different composition varying the interpass temperature in one case, in combination with the previously mentioned flux, according to Table 3.

Metallographic Study

Precisely due to the circumstance of having done the welds on different occasions, the methodologies employed for the microstructural analysis differed somewhat. In the case of the manual electrodes, to identify the microconstituents in the columnar zone, the technique previously applied by Evans in his first papers on the C-Mn system (E7018) (Refs. 17, 18) was used, in which the following three components were quantified: acicular ferrite [AF], lamellar components [LC], and primary ferrite [PF]. In the other samples the following constituents were identified: AF, ferrite with nonaligned second phase [FS(NA)], ferrite with aligned second phase [FS(A)], intragranular polygonal ferrite [PF(I)], and grain boundary ferrite [PF(G)], according to IIW Doc. IX-1533-88 (Ref. 19).

This study was conducted on the weld cross section in the columnar zone of the last bead and in the fine and coarse grain heat-affected zones, using Nital 2% and according to the description in Ref. 19. The proportion of reheated zones was measured at 500× in the region corresponding to the location of the Charpy V-notch — Fig. 1. The austenitic primary grain width (PAGW) was measured on the last bead of the samples at 100×. In order to quantify the microconstituents in the columnar zone, 10 fields of 100 points each were taken at 500×.

Mechanical Properties

After radiographic testing of all the test welds, an AWS tensile test specimen was machined out from SMAW, F1CAW (FCAW with F1 wire), F2CAW (FCAW with F2 wire), and SAW test coupons. On the other hand, a Minitrac (Ref. 20) tensile specimen (total length = 55 mm, gauge length = 25 mm, reduced section diameter = 5 mm, ratio of gauge length to diameter = 5:1) from the FaCAW (FCAW with Fa wire) and FbCAW (FCAW with Fb wire) specimens was extracted. A cross section for metallographic analysis, chemical analysis, and hardness survey was also obtained from each coupon as well as five Charpy-V specimens to measure the absorbed energy at –51°C (–60°F).

Table 3 — SMAW, FCAW, and SAW AWS Test Specimen Identification and Welding Parameters Used. SMAW: A5.5-81; FCAW: A5.29-98; SAW: A5.23-97

Sample	Shielding gas	Interpass T (°C)	Number of passes per layer	Total No. of passes/ No. layers	Current (A)	Tension (V)	Welding speed (mm/s)	Heat input (kJ/mm)
E10018M h	—	107	2	14/7	185	25	2.2	2.1
E10018M m	—	101	2	16/8	160	24	2.3	1.7
E10018M c	—	93	2	16/8	140	22	2.4	1.3
E11018M h	—	107	2	14/7	180	25	2.0	2.2
E11018M m	—	101	2	16/8	160	24	1.9	2.0
E11018M c	—	93	2	16/8	140	23	2.0	1.6
E12018M h	—	107	2	14/7	180	23	2.0	2.1
E12018M m	—	101	2	16/8	160	23	2.3	1.6
E12018M c	—	93	2	17/9	130	22	2.4	1.2
AWS req.	**—**	**107 to 93**	**2**	**NS/ 7 to 9**	**NS**	**NS**	**NS**	**NS**
FaC2	CO_2	140–150	2	12/6	238	29	3.6	2
FaC3	CO_2	140–150	3	18/6	193	26	4.1	1.5
FaA2	Ar/CO_2	140–150	2	12/6	234	28	3.4	2.2
FaA3	Ar/CO_2	140–150	3	18/6	197	25	4.6	1.2
FbC2	CO_2	140–150	2	12/6	265	27	4.1	1.9
FbC3	CO_2	140–150	3	18/6	241	26	6.4	1.1
FbA2	Ar/CO_2	140–150	2	12/6	260	27	4	1.9
FbA3	Ar/CO_2	140–150	3	12/6	235	26	5.6	1.2
F1C3	CO_2	150	3	18/6	150	25	2.9	1.3
F1C2	CO_2	150	2	12/6	150	25	1.9	2.0
F2C3	CO_2	150	3	12/6	230	27	6.2	1.0
AWS req.		**150**	**2 or 3**	**NS/ 5 to 8**	**NS**	**NS**	**NS**	**NS**
wire P3-D009	—	150	2	17/8	450	29	7	1.86
wire P4-D010	—	150	2	15/7	450	29	7	1.86
wire P4-D012	—	100	2	17/8	450	29	7	1.86
wire P14-D011	—	150	2	15/7	450	29	7	1.86
wire P18-D018	—	150	2	15/7	450	29	7	1.86
wire P18-D020	—	135	2 and 3	22/8	450	29	8.3	1.60
wire P20-D014	—	150	2	15/7	450	29.5	7	1.90
AWS req.	**—**	**150 ± 15**	**2 or 3**	**NS/ 5 to 8**	**450 ± 25**	**30 ± 1**	**6.0 ± 0.5**	**NS**

c: cold; m: medium; h: hot specimens. The plates were buttered with the same electrode used as filler and preset to avoid restraining. FCAW: electrode extension was 20 mm; gas flow: 20 L/min. SAW: all the wires in diameter 3.2 mm. NS: not specified.

The tensile properties were determined in the as-welded condition at room temperature, after baking the samples at 100°C (212°F) for 48 h to eliminate hydrogen. Toughness was also measured in the as-welded condition.

Results and Discussion

Chemical Composition

Table 4 shows the chemical composition corresponding to the weld metal samples employed to determine mechanical properties. The following can be seen:

SMAW. All the chemical requirements were satisfied for all the welding conditions employed. Figure 2 shows that as the heat input decreased higher values of C,

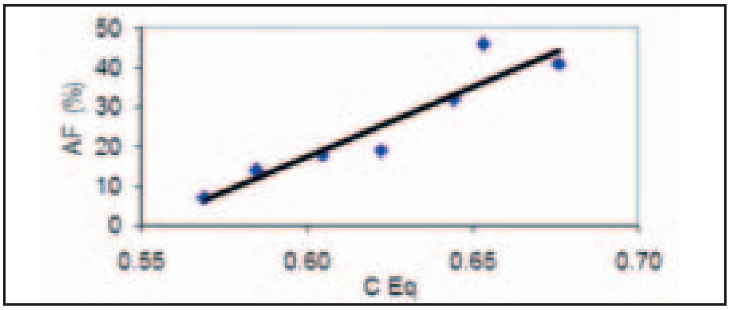

Fig. 5 — Acicular ferrite content vs. carbon equivalent.

$$\left(Ceq = C + \frac{Mn}{6} + \frac{(Cr + Mo + V)}{5} + \frac{(Cu + Ni)}{15}\right)$$

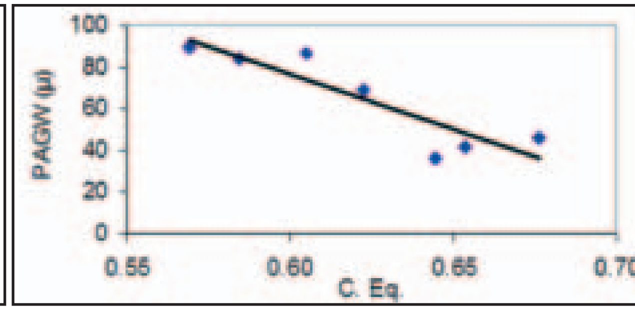

Fig. 6 — Primary austenite grain width vs. carbon equivalent.

$$\left(Ceq = C + \frac{Mn}{6} + \frac{(Cr + Mo + V)}{5} + \frac{(Cu + Ni)}{15}\right)$$

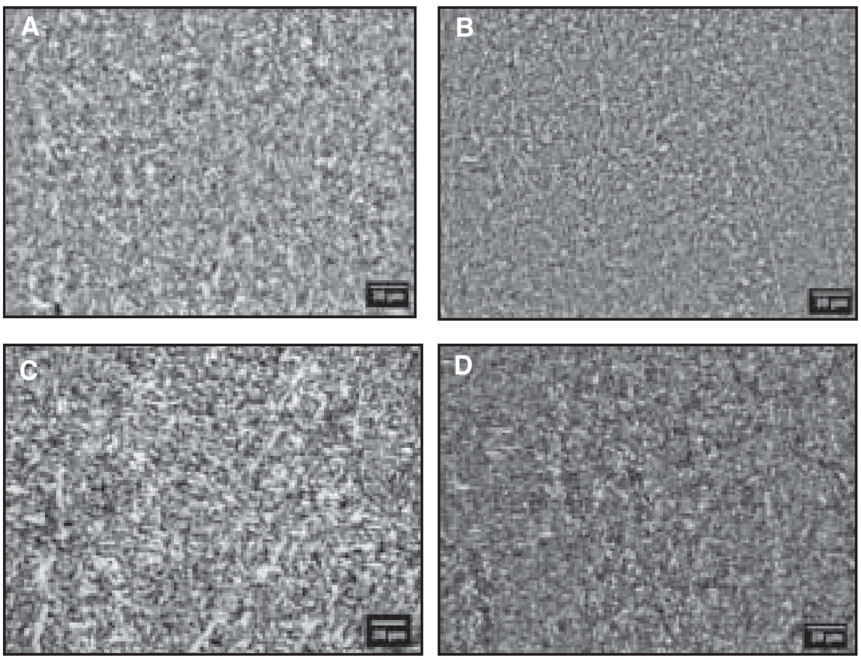

Fig. 7 — Optical micrograph of all-weld-metal columnar zones from different welding processes. A — E12018Mm; B — FbC3; C — F1C2; D — D018. Magnification: 500×. Metallographic etchant: Nital 2.

Mn, and Si were obtained, and oxygen and nitrogen levels were reduced, as previously found (Refs. 21, 22). Here, a trend in the chemical composition to vary with the heat input becomes apparent. Although the differences in the values obtained for the different elements probably were within the measurement error of the method, the systematic variations found could hardly be attributed to this error (around 5%).

FaCAW and FbCAW. Figure 3 shows that with both wires Mn and Si levels increased when the weld was done under the Ar-CO_2 gas mixture shielding, as compared to those made employing CO_2. For both wires Fa and Fb, the oxygen values were higher when using CO_2, this effect being slightly less marked for the wire Fb. The chemical composition of deposits made with wire Fa satisfied the requirements of the E101T5-K3 classification, but presented an excess in Mo according to E91T5-K2. In the case of wire Fb, Mo was above the required maximum, with the rest of the elements in agreement with E111T5-K3.

F1CAW and F2CAW. In the three test pieces the chemical requirements of the applicable standard were satisfied. The oxygen values were similar to those obtained in the manual electrode deposits E11018M and E12018M and significantly less than those corresponding to the weld deposits produced with wires Fa and Fb. The nitrogen values were surprisingly high and no explanation can be offered (Table 4).

SAW. Table 4 shows that the chemical requirements of the applicable standards were satisfied in all cases, these requirements being the same because they corresponded to the same wire M2.

The test conducted can be classified in four groups:

a) Cr free, low C, medium Mn: D009

b) Cr bearing, low C, medium Mn: D011, D012, and D010

c) Cr bearing, medium C, medium Mn: D018 and D020

d) Cr bearing, medium C, high Mn: D014

The oxygen values were similar to those found in the manual electrode deposits E11018M and E12018M and in those corresponding to wires F1 and F2.

Metallographic Study

SMAW. In Table 5A and Fig. 4A, it was observed that increasing the heat input an increase in the area fraction of the reheated zone at the expense of the columnar zone and an increase of the PAGW where this measurement was possible (samples E10018M and E11018M) took place. PAGW measurement in E12018M sample was not carried out due to the almost complete disappearance of the PF(G). For the three samples, the volumes of AF and LC increased at the expense of PF, as previously found by Evans (Ref. 17). It can be seen that the values of AF were much higher than those found in deposits of similar composition made with other welding processes; it is possible that the measurement of AF using this method included also FS(NA). The results of determinations made on two weld deposits from manual electrodes are presented in Table 5B. It is seen that when FS(A) and FS(NA) were discriminated, the AF levels were reduced leading to a percentage of microconstituents similar to those found in the samples of welds made with flux cored and submerged arc welding that were assessed using IIW Document (Ref. 19).

FaCAW and FbCAW. In Table 6 and Fig. 4B it is seen that, similarly to what was found for manual electrodes, an increase in heat input led to an increase in the reheated zone area fraction for both wires, as a general tendency. An increase in the PAGW of the columnar zone was determined when heat input increased for wire Fa, since for wire Fb this measurement was not possible due to the disappearance of PF(G). The values obtained for the PAGW were of the

Table 4 — All-Weld-Metal Chemical Composition from SMAW, FCAW, and SAW (all the elements expressed in wt-% except O and N, which are in ppm)

	C	Mn	P	S	Si	Ni	Cr	Mo	O	N	C. Eq.
E10018M h	0.042	1.34	0.025	0.013	0.34	1.90	0.08	0.38	552	129	0.48
E10018M m	0.041	1.45	0.028	0.013	0.40	1.97	0.08	0.40	538	120	0.51
E10018M c	0.056	1.49	0.029	0.013	0.40	1.97	0.09	0.40	511	87	0.53
Req. AWS	**0.10**	**0.75–1.70**	**0.030**	**0.030**	**0.60**	**1.40–2.10**	**0.35**	**0.25–0.50**	**NS**	**NS**	
E11018M h	0.040	1.58	0.015	0.007	0.44	1.94	0.30	0.33	360	86	0.56
E11018M m	0.042	1.63	0.016	0.007	0.48	1.97	0.31	0.35	321	84	0.58
E11018M c	0.045	1.68	0.016	0.008	0.54	1.98	0.31	0.34	315	71	0.59
Req. AWS	**0.10**	**1.30–1.80**	**0.030**	**0.030**	**0.60**	**1.25–2.50**	**0.40**	**0.25–0.50**	**NS**	**NS**	
E12018M h	0.043	1.56	0.022	0.016	0.43	2.25	0.45	0.43	377	98	0.63
E12018M m	0.048	1.62	0.018	0.013	0.45	2.20	0.43	0.42	349	95	0.63
E21018M c	0.051	1.68	0.020	0.012	0.46	2.13	0.46	0.40	314	87	0.65
Req. AWS	**0.10**	**1.30–2.25**	**0.030**	**0.030**	**0.60**	**1.75–2.50**	**0.30–1.50**	**0.30–0.55**	**NS**	**NS**	
FaC2	0.043	1.26	0.010	0.009	0.31	1.86	0.04	0.45	693	31	0.48
FaC3	0.035	1.14	0.010	0.009	0.27	1.90	0.04	0.45	755	28	0.45
FaA2	0.063	1.43	0.010	0.009	0.40	1.79	0.04	0.42	558	40	0.51
FaA3	0.048	1.47	0.010	0.009	0.43	1.79	0.04	0.44	573	26	0.51
FbC2	0.049	1.62	0.010	0.012	0.38	2.17	0.04	0.71	707	73	0.61
FbC3	0.047	1.66	0.010	0.012	0.41	2.17	0.04	0.73	715	65	0.62
FbA2	0.052	1.81	0.010	0.012	0.47	2.13	0.04	0.70	734	63	0.64
FbA3	0.047	1.76	0.010	0.011	0.45	2.16	0.03	0.71	716	58	0.63
E91T5-K2 req.	**0.15**	**0.50–1.75**	**0.03**	**0.03**	**0.80**	**1.25–2.60**	**0.15**	**0.35**	**NS**	**NS**	
E101T5K3/ E111T5-K3 req.	**0.15**	**0.75–2.25**	**0.03**	**0.03**	**0.80**	**1.25–2.60**	**0.15**	**0.25–0.65**	**NS**	**NS**	
F1C3	0.058	1.80	0.021	0.009	0.49	2.43	0.53	0.48	376	127	0.72
F1C2	0.054	1.64	0.020	0.009	0.40	2.38	0.53	0.47	398	132	0.69
F2C3	0.066	1.86	0.021	0.009	0.56	2.37	0.53	0.47	419	152	0.73
E120T5-K4 req.	**0.15**	**1.20–2.25**	**0.03**	**0.03**	**0.80**	**1.75–2.60**	**0.20–0.60**	**0.30–0.65**	**NS**	**NS**	
D009	0.07	1.63	0.015	0.011	0.18	1.67	0.06	0.52	*	*	0.57
D011	0.05	1.66	0.016	0.012	0.16	1.83	0.21	0.47	360	80	0.58
D012	0.07	1.67	0.017	0.009	0.29	1.89	0.18	0.56	340	70	0.62
D010	0.06	1.66	0.016	0.010	0.29	1.89	0.18	0.53	350	90	0.60
D018	0.10	1.74	0.022	0.008	0.37	1.79	0.20	0.52	*	*	0.65
D020	0.09	1.73	0.023	0.008	0.37	1.80	0.19	0.54	*	*	0.64
D014	0.08	1.86	0.018	0.011	0.43	2.04	0.21	0.54	*	*	0.68
F9/10/11/12A6-ECM2-M2 req.	**0.10**	**0.9–1.8**	**0.030**	**0.040**	**0.80**	**1.4–2.1**	**0.35**	**0.25–0.65**	**NS**	**NS**	

In all cases Sn, As, Sb, Co, Nb, and Al were lower than 0.01 wt-%.
* Without data.

$$Ceq = C + \frac{Mn}{6} + \frac{(Cr + Mo + V)}{5} + \frac{(Cu + Ni)}{15}$$

WELDING RESEARCH

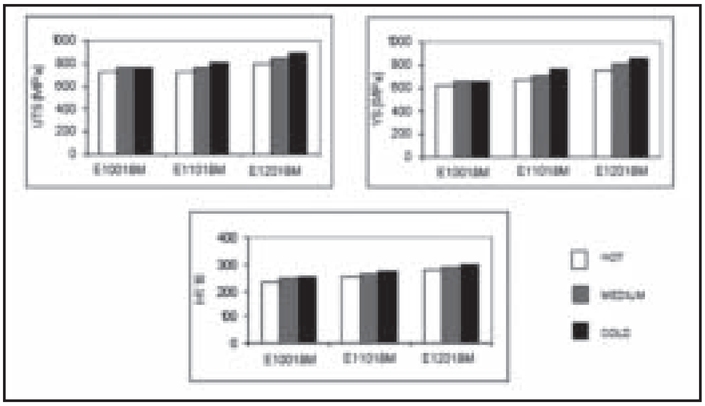

Fig. 8 — Heat input influence on UTS, YS, and HV of SMAW all-weld metal.

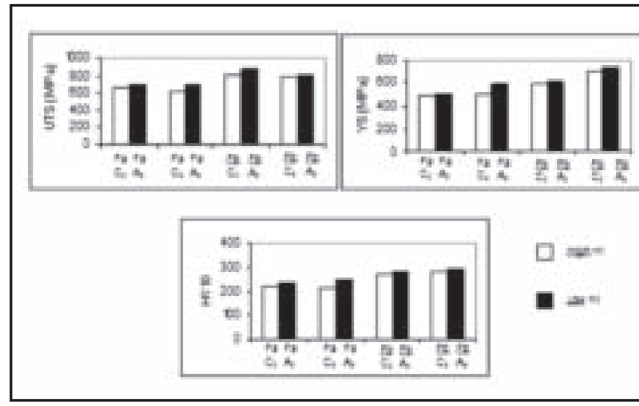

Fig. 9 — Heat input influence on UTS, YS, and HV of FCAW all-weld metal.

same order as those measured in samples E11018M of comparable oxygen content. For wire Fa, under gas mixture shielding, the largest proportion of AF and the lowest values of FS were obtained. For wire Fb under both shielding gases, the AF volumes were similar. In all samples, the main component was ferrite with second phase aligned or not.

The difference found between the microstructures of weld deposits from manual electrodes and flux cored wires may be due to the difference in oxygen level, which was significantly higher in the deposits made with the latter consumables. It is determined that AF increases when the oxygen is reduced within the ranges found in this work (Refs. 23–25).

F1CAW and F2CAW. Table 6 shows that sample F2C3 (low heat input obtained via an increment in the welding current and high welding speed) exhibited a higher columnar zone than F1C3 (low heat input and low welding current) and F1C2 (high heat input and low welding current); no important variation was found between F1C3 and F1C2 due to the difference in heat input. The PAGW was measured only in sample F1C3 (due to the disappearance of PF veins in deposits F2C3 and F1C2), and it was observed that it amounted approximately to deposits from SAW with similar oxygen levels.

Ferrite with second phase was the major component in the deposits of the three flux cored wires, due most certainly to the high Cr and Mo contents (Refs. 26, 27) presenting around 20% acicular ferrite.

SAW. Table 6 shows that the proportions of columnar zone did not disclose any relationship with the welding parameters. The AF values were very low in sample D009, with low C, Mn, and Ni, and without Cr addition, with the highest proportion of PF(G). Chromium-bearing samples D011, D012, and D010, all of which, with low carbon content, presented intermediate values of AF and PF(G). The largest proportion of AF and the lowest values of PF(G) corresponded to samples D018, D020, and D014 with higher C and Mn levels in agreement with previous findings (Refs. 16, 28, and 29). As a general tendency as the Ceq increased, there was an increase of AF (Fig. 5) and a decrease of the PAGW (Fig. 6), probably due to the simultaneous effects of C, Mn, and Cr (Refs. 16, 28–31). Sample D020, welded with low heat input and lower interpass temperature, showed the lowest PAGW due to the fact that the higher cooling rate limited its growing. This sample also showed the highest values of FS(NA).

Figure 7 shows typical columnar zone microstructures achieved with the different welding processes used in this work, where little difference among them can be observed.

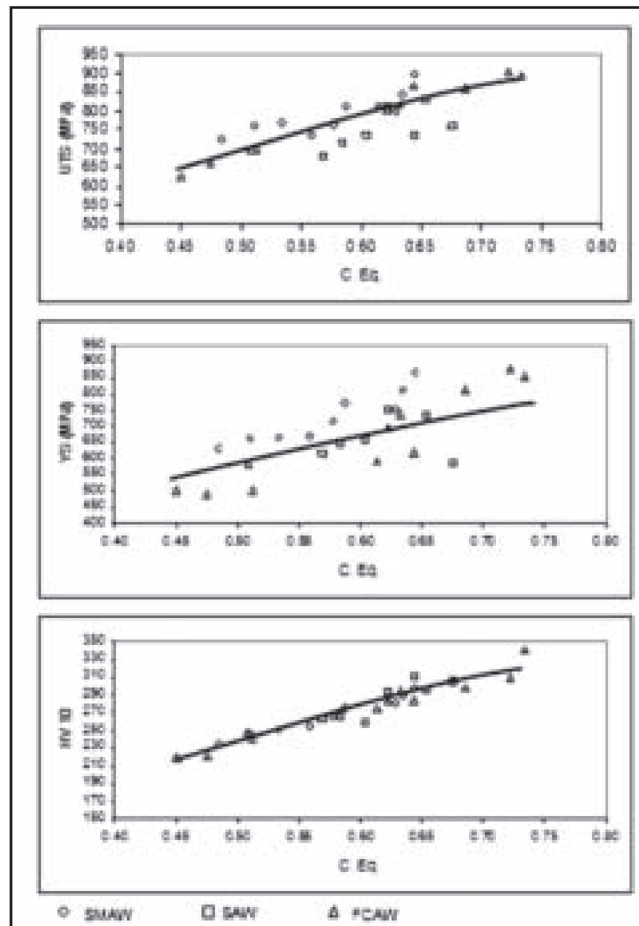

Fig. 10 — Carbon equivalent influence on UTS, YS, and HV of all-weld metals from all the welding processes. $\left(Ceq = C + \frac{Mn}{6} + \frac{(Cr+Mo+V)}{5} + \frac{(Cu+Ni)}{15}\right)$

Tensile Properties and Hardness

Table 7 presents the tensile properties obtained with all the welding processes employed.

SMAW. Figure 8 shows that for the three electrodes, as the heat input increases, a reduction in hardness, tensile strength, and yield strength took place in agreement with the chemical analysis, as was to be expected (Ref. 21). In all the samples corresponding to the three electrodes, the elongation values were above the required minimum.

In the case of the E10018M electrode, all the tensile and yield strength requirements were satisfied for the three samples, which mean that within the variation imposed on heat input, the change in tensile properties maintained satisfactory values. On the other hand, with electrode E11018M, the required minimums in tensile and yield strengths were not met by the "hot" sample, while yield strength was above the maximum with the "cold" sample. Only with the intermediate sample was it possible to satisfy the standard spec-

Table 5A — Results of Metallographic Studies, Carried Out According to the Methodology Used by Evans (Refs. 13 and 14)

Electrode	Heat input (kJ/mm)	CZ (%)	RZ (%)	PAGW (μ)	AF (%)	LC (%)	PF (%)
E10018M h	2.1	25	75	140	62	20	18
E10018M m	1.7	42	58	125	58	16	26
E10018M c	1.3	55	45	110	56	14	30
E11018M h	2.2	18	82	216	74	20	6
E11018M m	2.0	25	75	189	72	19	9
E11018M c	1.6	42	58	159	66	17	17
E12018M h	2.1	36	64	(*)	64	26	10
E12018M m	1.6	45	55	(*)	62	25	13
E12018M c	1.2	50	50	(*)	59	22	19

(*) It was not possible to perform this measurement due to the loss of the grain boundary ferrite veins.
CZ: columnar zone; RZ: reheated zone; PAGW: prior austenite grain width.
Columnar zone microconstituents: AF: acicular ferrite; PF: primary ferrite; LC: lamellar components.

Table 5B — Results of Metallographic Studies Performed with the Two Methodologies on the Same Samples

	New results (Ref. 15)					Previous results (Refs. 13 and 14)		
Electrode	AF	PF(G)	PF(I)	FS(A)	FS(NA)	AF	LC	PF
E11018M m	36	8	15	2	39	72	19	9
E12018M m	36	13	14	3	34	62	25	13

AF: acicular ferrite; PF(G): grain boundary ferrite; intragranular polygonal ferrite; FS(A): ferrite with second phase, aligned; FS(NA): ferrite with second phase, not aligned; LC: lamellar components; PF: primary ferrite.

Table 6 — Results of Metallographic Studies Perfomed According to IIW Doc. IX-1533-88 (Ref. 19)

Electrode	Heat input (kJ/mm)	CZ (%)	RZ (%)	PAGW (μ)	AF (%)	FS(A) (%)	FS(NA) (%)	Total FS (%)	PF(G) (%)	PF(I) (%)	Total PF (%)
FaC2	2.0	54	46	107	15	3	53	56	22	7	29
FaC3	1.5	62	38	97	7	15	37	52	36	5	41
FaA2	2.2	73	27	120	45	2	28	30	13	12	25
FaA3	1.2	55	45	103	37	6	31	37	12	14	26
FbC2	1.9	58	42	(*)	26	3	48	51	5	18	23
FbC3	1.1	77	23	(*)	23	4	56	60	3	14	17
FbA2	1.9	58	42	(*)	16	0	75	55	0	9	9
FbA3	1.2	70	30	(*)	21	2	80	82	1	16	17
F1C3	1.3	50	50	46	23	8	63	71			6
F1C2	2.0	47	53	(*)	9	8	73	81			10
F2C3	1.0	70	30	(*)	29	8	53	61			10
D009	1.86	80	20	89	7	11	36	47	37	9	46
D011	1.86	51	49	84	14	26	42	68	12	6	18
D012	1.86	40	60	69	19	23	36	59	13	9	22
D010	1.86	39	61	87	18	13	43	56	16	10	26
D018	1.86	30	70	42	46	4	37	41	3	10	13
D020	1.60	52	48	36	32	2	50	52	2	14	16
D014	1.90	40	60	46	41	9	38	47	5	7	12

(*) It was not possible to perform this measurement due to the loss of the grain boundary ferrite veins.
CZ: columnar zone; RZ: reheated zone; PAGW: prior austenite grain width.
Columnar zone microconstituents: AF: acicular ferrite; PF(G): grain boundary ferrite; PF(I): intragranular polygonal ferrite; PF: primary ferrite; FS: ferrite with second phase; FS(A): ferrite with second phase, aligned; FS(NA): ferrite with second phase, not aligned.

ification. With electrode E12018M, the "hot" sample did not meet the minimum of tensile strength and the "cold" sample exceeded yield strength requirements, while only the intermediate sample satisfied the requirements.

These results show that mechanical properties of the weld metal deposited by the last two electrodes were sensitive to the heat input, which in this case was essentially modified with moderate changes in current intensity (Table 3). It is worth noting that there was a narrow range of heat input within which mechanical property requirements were met. These variations in the heat input influenced the microstructural development, affecting mostly the fraction of reheated zone (RZ) and the PAGW. The hardness level in the RZ was lower than in the columnar zone (CZ), as was observed previously (Ref. 21). This could explain the reduction in tensile and yield strength results as the heat input increased.

Table 7 — All-Weld-Metal Mechanical Property Results

Electrode	Heat Input (kJ/mm)	UTS (MPa)	YS (MPa)	E (%)	Ch-V at –51°C (J)	Average Hardness (HV 10)
E10018M h	2.1	724	632	23.4	53	234
E10018M m	1.7	760	660	22.8	56	246
E10018M c	1.3	766	665	22.0	73	251
AWS req.		**690 min.**	**610–690**	**20 min.**	**27 min.**	**NS**
E11018M h	2.2	734	669	23.1	55	255
E11018M m	2.0	764	715	23.6	60	264
E11018M c	1.6	810	770	21.6	45	275
AWS req.		**760 min.**	**680–760**	**20 min.**	**27 min.**	**NS**
E12018M h	2.1	796	754	20.7	55	281
E12018M m	1.6	845	814	19.7	50	289
E12018M c	1.2	895	866	19.0	54	297
AWS req.		**830 min.**	**745–830**	**18 min.**	**27 min.**	**NS**
FaC2	2.0	661	492	28	74	221
FaC3	1.5	625	502	20	47	219
FaA2	2.2	699	503	20	83	239
FaA3	1.2	699	587	21	59	248
E91T5-K2 req.	**NS**	**620–760**	**540 min.**	**17 min.**	**27 min.**	**NS**
E101T5-K3 req.	**NS**	**690–830**	**610 min.**	**16 min.**	**27 min.**	**NS**
FbC2	1.9	812	594	18.8	61	274
FbC3	1.1	801	695	18.8	44	283
FbA2	1.9	866	619	17.2	54	284
FbA3	1.2	815	739	18.4	64	293
E111T5-K3 req.	**NS**	**760–900**	**680 min.**	**15 min.**	**27 min.**	**NS**
F1C3	1.3	903	879	19	59	309
F1C2	2.0	856	813	20	39	298
F2C3	1.0	891	854	18	31	341
E120T5-K4 req.	**NS**	**830–970**	**750 min.**	**14 min.**	**27 min.**	**NS**
D009	1.86	680	615	23	71	262
D011	1.86	715	647	24	60	265
D012	1.86	810	749	23.4	101	292
D010	1.86	735	655	25	99	258
D018	1.86	827	734	23	66	295
D020	1.60	735	—	5.2	79	310
D014	1.90	757	586	NO	84	305
F9A6-ECM2-M2 req.	NS	**620–760**	**540 min.**	**17 min.**	**27 min.**	**NS**
F10A6-ECM2-M2 req.	NS	**690–830**	**610 min.**	**16 min.**	**27 min.**	**NS**
F11A6-ECM2-M2 req.	NS	**760–900**	**680 min.**	**15 min.**	**27 min.**	**NS**
F12A6-ECM2-M2 req.	NS	**830–970**	**750 min.**	**14 min.**	**27 min.**	**NS**

UTS: ultimate tensile strength, YS: yield strength, E: elongation, Ch-V: Charpy-V impact, NS: not specified.

The welding current range employed (between 140 and 180 A) is within what is usually adopted for these types of electrodes in 4 mm diameter, and it is slightly lower than that indicated in Table A.3 of Annex A of the corresponding AWS Standard (Ref. 1) of 135–185 A. Consequently, if samples are welded using this allowable current range, larger differences in tensile properties will be obtained making the satisfaction of the tensile property standard requirements even more difficult.

FaCAW and FbCAW. Figure 9 shows that for both wires the tensile and yield strengths, as well as hardness values, decreased with the protection of CO_2 with respect to the Ar-CO_2 gas mixture in agreement with the chemical composition. All the samples satisfied the elongation requirements. Nevertheless, for both wires, only with heat inputs of 1.2 kJ/mm or less, the minimum yield strength requirements for E91T5-K2 and E111T5-K3 classifications were reached. In the case of the latter, hardness in CZ was higher than in the RZ. The larger proportion of CZ and the probably lower PAWG could explain the increase in the yield strength for these samples.

With wire Fa, under Ar/CO_2 shielding and with three passes per layer, the requirements of classification E91T5-K2 were satisfied (but not those of chemical composition, since the Mo content was above the maximum specified). The sample welded with two passes per layer under the same shielding did not meet the yield strength requirement. On the other hand, no weld deposit reached the tensile requirements of the E101T5-K3 classification, notwithstanding the fact that they satisfied the chemical requirements. These deposits showed a reasonable variation in tensile strength (625 to 699 MPa), but a large variation in yield strength (492 to 587 MPa), which would prevent the satisfaction of the narrow specification range for the equivalent manual electrode

(E10018M) that in this work met the requirement. For this wire, in order to increase the tensile strength without exceeding the allowed Mo maximum, or alternatively to satisfy the tensile requirements of the E101T5-K3 classification without modification in the Mo content, an increase in Mn could be explored but since this element is furnished not only by the core material but also by the steel sheath, there is danger of overalloying and going over the allowed range of 1.75% Mn with a possible deterioration in toughness. Something similar took place with wire Fb. Tensile requirements of E111T5-K3 classification were satisfied (although not that of chemical composition due to an excess in Mo) with the weld samples produced with both shielding gases using three passes of layer. Tensile strength in these samples resulted somewhat lower, but the yield strength was higher and over the required minimum. The variations found in tensile strength values when the heat input was changed was reasonable (801 to 866 MPa) but the range in yield strength values was ample (594 to 739 MPa). This implies that this consumable would have not met the yield requirements of the equivalent manual electrode E11018M (range = 80 MPa, Table 2).

F1CAW and F2CAW. The three deposits obtained with this process satisfied the tensile requirements of E120T5-K4 classification. Chemical composition was close to the upper limit of the standard, which is at least a potentially dangerous condition taking into consideration the usual variations in composition found in electrode manufacturing. Hardness values were the highest obtained comparing all the processes, in correlation with tensile values.

SAW. Weld D009 did not meet tensile requirements in any of the two classifications: F10A6-ECM2-M2 and F11A6-ECM2-M2. The alloying achieved was not enough for this procedure. It would have satisfied the requirements of F9A6-ECM2-M2 with tensile strength 620 to 760 MPa and yield strength of 540 MPa minimum.

Weld D011 did not satisfy the requirements of classification F11 but did those of F10, which stresses the necessity of Cr additions to raise the tensile strength. However, with the same wire and reducing the interpass temperature without any change in heat input, weld D012, F11 requirements were satisfied. These results confirm that by using lower interpass temperatures higher tensile strength values can be obtained as previously found (Ref. 32).

Weld D010, of a chemical composition close to that of D011, but with higher Si and Mo levels, gave similar results although with somewhat higher tensile and yield strengths.

With weld D018, with higher C and with the same Cr level, the requirements of F11 were comfortably satisfied, so it was necessary to raise the tensile strength through an increase in C content. When using the same wire to weld a test piece with lower heat input, weld D020, the tensile test was invalid and the results were consequently discarded.

With the high-Mn wire, weld D014 failed the tensile test since it broke in a completely brittle manner, with virtually no elongation, and the results were again discarded (although this was not the case for impact test results obtained from these last two samples).

These results show that as was expected, when the alloy content increases, tensile strength also increases up to a point close to the upper limit of the M2 wire specification (see Table 4), thus leaving little margin for further increase via alloy content. The marked sensitivity to welding procedure parameters was also made apparent for these deposits.

As tensile strength increased, hardness increased except for the samples that failed in the tensile test, which presented maximum hardness values.

For all the welding processes, as International Institute of Welding-IIW Carbon Equivalent-CE (Ref. 33) increased, hardness, tensile strength, and yield strength increased, as can be seen in Fig. 10.

Charpy V-Notch Impact Properties

Table 7 shows Charpy-V impact test result obtained at –51°C (–60°F), since this is the specified temperature by the relevant standards for this type of deposits obtained with all the processes considered in this work.

SMAW. Impact test requirements were comfortably satisfied in all cases for any condition of welding procedure. High values of toughness had already been found by the authors in previous studies on this system in which the effects of variations in Mn (Ref. 28), C (Ref. 31), Cr for two different levels of Mn (Ref. 30), and Mo for two different levels of Mn (Ref. 34) were analyzed, and in which it was observed that individually, Mn level could be increased up to 1.7%, C level up to 0.10%, Cr level up to 0.5%, and Mo level up to 0.5% without deleterious effect on toughness.

FaCAW and FbCAW. All the welded samples with these consumables also satisfied comfortably the impact requirements. No single value under the required minimum of 27 J was found. The lowest average value, corresponding to wire Fb, was 44 J, obtained with CO_2 shielding and three passes per layer.

F1CAW and F2CAW. The three welded samples met the standard requirements in spite of the very high tensile values and nitrogen contents exhibited by these welds. The lowest impact value was 27 J for weld F2C3; this result may be related to the highest hardness and percentage of columnar zone measured in this sample.

SAW. All the welds tested comfortably met the minimum impact requirements for any of the welding conditions considered, including those welds that failed to pass the tensile test. The lowest Charpy-V impact value obtained was 53 J in welded samples D011 and D018, and the lowest average was 60 J for weld D011. For all the procedure variations analyzed, the mean and individual impact values obtained in all these samples were within the range reported by the consumables manufacturers (Refs. 35–38).

AWS Standard Requirements Corresponding to the Different Welding Processes for the Same Type of Weld Deposit

Table 2 presents the tensile and impact property requirements for the deposits considered. It can be seen that for a given type of weld metal (see chemical composition, Table 1) the requirements differ notwithstanding the fact that the minimum values for tensile and yield strength are the same but differing the ranges within which these values must fall.

Besides the example mentioned in the Introduction (E11018M and E110T5-K3 or F11A6-ECM2-M2), E12018M and E120T5-K4 or F12A6-ECM2-M2 are also presented. Although it is nearly the same type of deposit according to their chemical composition, the manual electrode must satisfy a minimum of tensile strength (830 MPa) and a yield strength range (745–830 MPa) of only 85 MPa while the FCAW electrode or the combination flux/wire for SAW have a wide range for tensile strength requirement (830–970 MPa) and a single minimum value for yield strength (750 MPa). The same applies to E10018M and E101T5-K3 or F10A6-ECM2-M2.

The elongation requirements are not the same for different processes for the same type of deposit. So, how to interpret that a given welded joint in a welded fabrication requires 20% minimum elongation for manual electrodes and 15% for FCAW tubular electrodes, or for the wire/flux combination in SAW?

On the other side, impact requirements of AWS standards for these type of materials impose exactly the same requirement of 27 J minimum at –51°C (with no single value under 20 J), which as has already been shown, were comfortably satisfied by all the welding processes analyzed.

This implies that if it is necessary to replace SMAW EXXX18M consumables with FCAW or SAW ones, to increase efficiency, in order to produce similar weld metal it may not be advisable to switch to a chemical composition equivalent consumable for SAW or FCAW, due to the less stringent requirements they present. (It is necessary to take into account that the SMAW consumables used in this work respond to military special requirements; military specifications for FCAW and SAW consumables of this type do not exist in AWS filler metal standards.)

Conclusions

From the analysis of the results obtained in this work, it is seen that with all the processes and welding procedures considered, the impact requirements of the appropriate standards were comfortably satisfied. However, fulfillment of tensile properties proved to be much more difficult. In several cases, it became necessary to exceed the specified chemical composition in order to achieve the required minimum tensile strength.

On the other side, it is not only about the manual electrode deposits being more sensitive to heat input as shown by the tensile test results, but rather that for these consumables the tensile requirements are more stringent (as they are military special specifications) than for the equivalent consumables in chemical composition employed in the other welding processes.

An important practical implication of the observed variation of mechanical properties as function of welding conditions is that frequently the welding conditions used for welding procedure qualification are different from those used for consumable classification as required by the different AWS specifications. Therefore, the user of the welding consumable needs to be aware of this fact when selecting consumables and when conducting qualification of the welding procedure.

Acknowledgments

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