The Effect of Welding Parameters on High-Strength SMAW All-Weld-Metal — Part 2: AWS E10018-M and E12018-M

The influence of welding parameters on tensile strength of E10018-M and E12018-M electrodes welded to AWS A5.5-81 requirements was investigated

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ABSTRACT. Three AWS A5.5-81[1] all-weld-metal test assemblies were welded, each with one of E10018-M and E12018-M type electrodes from standard production batches, varying the welding parameters, in such a way as to use high heat input and high interpass temperature (hot), medium heat input and medium interpass temperature (medium) and low heat input and low interpass temperature (cold). Mechanical properties and metallographic studies were performed in the as-welded condition. The following results were achieved: the three all-weld-metals from E10018-M electrodes satisfied the AWS requirements, despite the fact that the measured properties varied slightly. With the E12018-M electrodes, the medium test specimen was the only one that fulfilled the AWS requirements. The cold test specimen showed a yield strength that exceeded the maximum requirement of the norm and the hot specimen did not achieve the minimal value of tensile strength. All the test specimens satisfied elongation and toughness requirements. Metallographic studies showed that as the heat input increased, the percentages of recrystallized zones increased, the grain size became larger and, in the columnar regions, there was a small increment of acicular ferrite and ferrite with second phase at the expense of primary ferrite. These results showed the E10018-M alloy to be markedly less sensitive to the variations of heat input than the E12018-M. With the E12018-M electrode, it is necessary to weld under strict control and with precise conditions, as found for E11018-M electrodes in Part 1 of this work, in which the same study was performed with the latter type of electrode.

Introduction

As mentioned in the first part of this work (Ref. 1), obtaining all-weld-metal good toughness with manual electrodes of the type AWS A5.5-81 E10018/ E11018/ E12018-M does not present many problems if a good formula and an adequate chemical composition are achieved. Several papers (Refs. 2–4) show it is easy to get optimum toughness with very low carbon levels (less than 0.05%), manganese between 1.0 and 1.4%, nickel 2.0% and molybdenum 0.30%. With higher carbon (up to 0.10%) and manganese (up to 1.7%) and adding chromium (up to 0.75%), it is still possible to have good toughness values that satisfy AWS A5.5-81 requirements: 27 J minimum at –51°C (–60°F) (Ref. 5). The problem is obtaining the appropriate tensile properties in accordance with the AWS standard (Ref. 5) — Table 1.

Part 1 (Ref. 1) of this work showed the influence of the welding parameters used within the requirements of the AWS standard (Ref. 5) on the all-weld-metal mechanical properties of an E11018-M type electrode. It was shown for the same batch of electrodes, welded under three different conditions: high heat input and high interpass temperature (hot), medium heat input and medium interpass temperature (medium) and low heat input and low temperature (cold). Toughness was not markedly influenced, but the tensile properties varied such that only the medium test specimen satisfied the AWS requirements. The cold one presented very high yield strength; it exceeded the maximum value requested. The hot one, on the other hand, showed figures for yield and tensile strengths that did not achieve the minimum required values. Minimal elongation was obtained with all test specimens. It is important to take into account that the three test assemblies were welded using amperages to achieve good operational characteristics of the electrodes. The welding procedure was in accordance with the specifications of AWS A5.5-81 standard (two beads per layer, 7–9 layers).

In this new work, E10018-M and E12018-M electrodes (the inferior and superior immediate categories of E11018-M electrode[2]) were tested at the hot, medium and cold conditions used in Part 1.

KEYWORDS
E10018-M
E12018-M
Weld Toughness
Charpy V-Notch
Welding Parameters

[1] *It must be taken into account that this work, the second part of a program that started in Ref. 1, was performed during 1994 (actually preliminary results were discussed at the International Institute of Welding Sub commission II-A as Doc. II-A-934-94), according to AWS A5.5-81 (Ref. 5), which was revised as A5.5-96 (Ref. 6). It is important to note this fact because, in the 1996 version, joint preparation has been changed from the 1981 version (45° included angle and ¼-in. [12.7-mm] root opening) to 20° included angle and ⅜-in. [16-mm] root opening. As this is an important variation related to the essence of this work, it would not be correct to affirm that the results can be extrapolated to the new test specimen design: see Conclusions.*

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[2] *See Table 2, page 4, of AWS A5.5-81, Ref. 5 and/or Table 2, page 5, of ANSI/AWS A5.5-96, Ref. 6; E10018-M is the previous and E12018-M the subsequent electrode classification category with respect to E11018-M electrode.*

Experimental Procedure

Electrodes

Low hydrogen iron powder E10018-M and E12018-M electrodes from standard production were used. The core wire diameter was, in both cases, 4 mm and the coating factors D/d (coating diameter/wire diameter) were 1.65 and 1.70, respectively. The electrodes were redried for one hour at 350°C (662°F) before being used to uniform the starting conditions. (This was done because the electrodes belonged to standard batches of two different consumables, elaborated in different occasions, originally dried in production at 420°C (788°F) and packed in polyethylene bags and cardboard boxes.)

Weld Preparation

The weld preparation for all test specimens was per AWS A5.5-81, using base metal thickness of ¾ in. (19 mm). Welding was performed in the flat position and two beads per layer were deposited with only one for the first layer, as per the standard.

Table 1 — AWS A5.5-81 E10018-M and E12018-M Electrode Tensile Property Requirements*

Electrode	Tensile Strength (MPa)	Yield Strength (MPa)	Elongation (%)	Charpy V-Notch Impact at –51°C (J)
E10018-M	690	610–690	20	27
E12018-M	830	745–830	18	27
	min		min	min

*ANSI/AWS A5.5-96 requires the same all-weld metal mechanical property values.

The welding parameters employed for the six test assemblies (one set of three test assemblies with E10018-M and another set of three with E12018-M electrodes) are presented in Table 2, as well as the heat inputs that were used. The preheat and interpass temperatures were chosen always to be within the range established by the AWS A5.5-81 standard. Welding speed was determined by measuring bead length vs. arc time. The variation found in speed determination along the test coupon welding was maximum ±12%.

Mechanical Testing

From each test assembly, one tensile specimen (with a 4:1 gage length to diameter ratio and located exactly as required by AWS A5.5-81), one section for metallographic studies and five Charpy V-notch specimens were obtained. Tensile and toughness properties were tested in the as-welded condition, at room temperature and at –51°C (–60°F), respectively. Hardness Vickers (HV10) was measured from the top and along the center line of the metallographic specimen.

Table 2 — Welding Parameters

Electrode	E10018-M			E12018-M			AWS
Condition	Hot	Medium	Cold	Hot	Medium	Cold	—
Heat input (KJ/mm)	2.1	1.7	1.3	2.1	1.6	1.2	—
Amperage (A)	185	160	140	180	160	130	—
Arc voltage (V)	25	24	22	23	23	22	—
Interpass temperature (°C)	107	101	93	107	101	93	93–107
Welding speed (mm/s)	2.2	2.3	2.4	2.0	2.3	2.4	—
Number of layers	7	8	8	7	8	9	7–9

Table 3 — All-Weld-Metal Chemical Composition Results and AWS Requirements

Electrode	Heat Input (KJ/mm)	C	Mn	P	S	Si	Ni	Cr	Mo	V	O (ppm)	N (ppm)
	Hot	0.042	1.34	0.025	0.013	0.34	1.90	0.08	0.38	<0.010	552	129
E10018-M	Medium	0.041	1.45	0.028	0.013	0.40	1.97	0.08	0.40	<0.010	538	120
	Cold	0.056	1.49	0.029	0.013	0.40	1.97	0.09	0.40	<0.010	511	87
AWS requirements*		0.10	0.75–1.70	0.030	0.030	0.60	1.40–2.10	0.35	0.25–0.50	0.05		
	Hot	0.040	1.58	0.015	0.007	0.44	1.94	0.30	0.34	<0.010	361	84
		0.040	1.57	0.015	0.007	0.44	1.94	0.30	0.32	<0.010	360	88
E11018M	Medium	0.051	1.60	0.014	0.008	0.48	1.86	0.29	0.32	<0.010	321	84
(Ref. 1)		0.043	1.63	0.016	0.007	0.48	1.97	1.31	0.35	<0.010		
	Cold	0.040	1.67	0.016	0.007	0.54	1.92	0.30	0.34	<0.010	321	76
		0.050	1.70	0.016	0.009	0.54	2.04	0.32	0.34	<0.010	309	67
AWS requirements*		0.010	1.30–1.80	0.030	0.030	0.60	1.25–2.50	0.40	0.25–0.50	0.05		
	Hot	0.043	1.56	0.022	0.016	0.43	2.25	0.45	0.43	<0.010	377	98
E12018-M	Medium	0.048	1.62	0.018	0.013	0.45	2.20	0.43	0.42	<0.010	349	95
	Cold	0.051	1.68	0.020	0.012	0.46	2.13	0.46	0.40	<0.010	314	87
AWS requirements*		0.10	1.30–2.25	0.030	0.030	0.60	1.75–2.50	0.30–1.40	0.30–0.55	0.05		

*AWS A5.5-81 and ANSI/AWS A5.5-96 standards require the same values. Single values are maximum.

Metallography

Examinations of transverse sections (etched in a 2% solution of nital) were carried out on the top beads and the adjacent supercritically reheated zones, as described previously (Refs. 2–4) and according to Ref. 7.

Results

The tables and/or figures include results from E11018-M type electrode testing (Ref. 1), for discussion purposes.

Chemical Composition

The chemical analyses of the two sets of three all-weld-metal deposits are presented in Table 3.

All the compositions satisfied the requirements of AWS A5.5-81 (Ref. 5) Table 3 and were within the optimum ranges for each element and for each electrode type E10018-M and 12018-M, as was found in previous studies (Refs. 2–4).

The oxygen and nitrogen values increased with the heat input. The higher amperage and voltage might result in more O and N in the arc environment (Refs. 8, 9) as more time was available for the weld pool to absorb O and N from the environment (Ref. 9).

It is interesting to note that, due to the different coating factor, mineral base and Mn content of the coating of the E10018-M and E12018-M commercial electrodes, two different levels of oxygen were achieved: 511 to 552 ppm and 314 to 377 ppm, respectively. In spite of that fact, both are iron powder basic coating electrodes according to EXXX18-X classification.

In both cases, it can be seen that as the heat input increased, the values of Mn and Si slightly decreased, due to the higher oxidation of these two elements, which are not only alloying elements but also deoxidants in the arc. This effect was previously found by Evans (Refs. 10, 11) and Vercesi, *et al.* (Ref. 1). The two test specimens, welded with the intermediate conditions, presented intermediate Mn and Si values.

As a general tendency, carbon figures decreased with the increase of the heat input for the same reasons.

Table 4 — Percentages of Columnar and Refined Region All-Weld-Metal Lying Ahead of the Charpy V-Notch

Electrode	Heat input (KJ/mm)	Columnar Zone (%)	Refined Zone (%)
E10018-M	2.1	25	75
	1.7	42	58
	1.3	55	45
E11018-M (Ref. 1)	2.2	18	85
	2.0	25	75
	1.6	42	58
E12018-M	2.1	36	64
	1.6	45	55
	1.2	50	50

Table 5 — Prior Austenite Grain Size (Width) in the As-Deposited Columnar Regions of the Final Pass

Electrode	Heat input (KJ/mm)	Width of Prior Austenite Grain (u)
E10018-M	2.1	140
	1.7	125
	1.3	110
E11018-M (Ref. 1)	2.2	216
	2.0	189
	1.6	159

Note: For E12018-M electrode, it was not possible to perform the measurement due to the loss of the grain boundary ferrite veins.

Table 6 — Quantitative Survey of Different Microstructural Constituents within the Columnar Region of the Top Passes

Electrode	Heat input (KJ/mm)	Acicular Ferrite (%)	Ferrite with Second Phase (%)	Primary Ferrite (%)
E10018-M	2.1	62	20	18
	1.7	58	16	26
	1.3	56	14	30
E11018-M (Ref. 1)	2.2	74	20	6
	2.0	72	19	9
	1.6	66	17	17
E12018-M	2.1	64	26	10
	1.6	62	25	13
	1.2	59	22	19

Metallographic Examination

General

Table 4 presents the zonal distribution along the vertical central line, in the Charpy V-notch location with the three heat inputs employed, in the two sets. It can be seen that as the heat input decreased, the percentages of columnar zone increased, at the expense of the refined zones, as was shown before (Refs. 1, 10, 11).

As-Deposited Weld Metal

Examination of as-deposited weld metal with low magnification revealed the width of the prior/columnar austenite grains increased as the heat input increased, Table 5, as previously indicated (Refs. 1, 10–12). The prior austenite grain size (width) in the as-deposited columnar regions of the final pass, was measured only for the E10018-M all-weld-metal. It was not possible to carry out the same measurement in E12018-M all-weld metal because the veins of grain boundary ferrite disappeared as the degree of alloy increased (addition of Cr and increment of Mn and Ni, Table 3), as shown earlier (Refs. 13–16).

The last deposited beads were examined at 100X and 200X and quantitative metallographic measurements were performed at 400X, identifying the following major microstructural components:

- primary ferrite
- acicular ferrite
- ferrite with second phase

With higher magnification, other constituents can be identified and quantified (Ref. 16).

In Table 6, the point count results are given; it can be observed that as the heat input increased, there was a slight increase of both acicular ferrite and ferrite with second phase, either aligned or nonaligned at the expense of primary ferrite. This is in accordance with previous results (Ref. 1).

Typical microphotographs of both electrodes columnar regions are shown in Fig. 1 for E10018-M (100X) and Fig. 2 for E12018-M (200X).

Reheated Weld Metal

It was not possible to differentiate the coarse from the fine refined zones or to measure the ferrite grain size because under the magnification used, it was too small; see the photomicrographs presented in Fig. 3A for E10018-M and Fig. 3B for E12018-M, both at 200X. However, the general decrease in ferrite grain size when the heat input decreased is noticeable.

Mechanical Properties

Hardness Testing

Average hardness values obtained from the metallographic sections, are presented in Fig. 4 for E10018-M and E12018-M electrodes.

With both electrodes, as the heat input increased, hardness values decreased, in accordance with previous studies (Refs. 1, 12, 17, 18). The figures obtained with the E12018-M electrodes are higher than those obtained with the E10018-M ones, as expected, due to the higher alloy content — Table 3. The values obtained before (Ref. 1) with E11018-M electrode are between those of E12018-M and E10018-M. It was not possible to explain the decline in hardness that appeared in the center of the transversal sections, for both electrodes, taking into account the variation of welding speed and other welding conditions, during the specimen welding.

Soundness Test Results

The two sets of three test assemblies were radiographed in accordance with AWS A5.5-81 (and also with ANSI/AWS A5.5-96) and presented optimum results — no apparent defects.

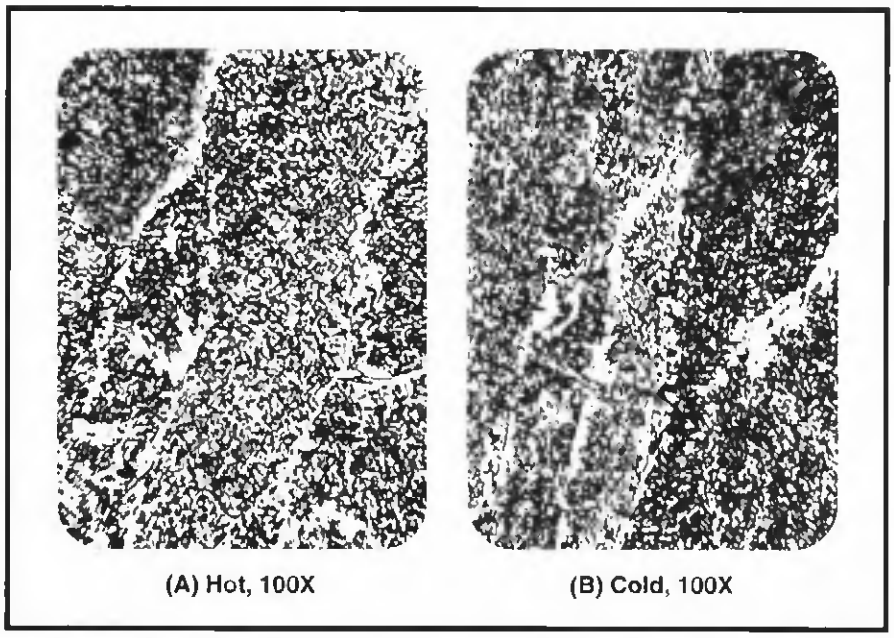

Fig. 1 — Photomicrographs of columnar zones (E1001B-M): A — Hot 100X; B — Cold 100X.

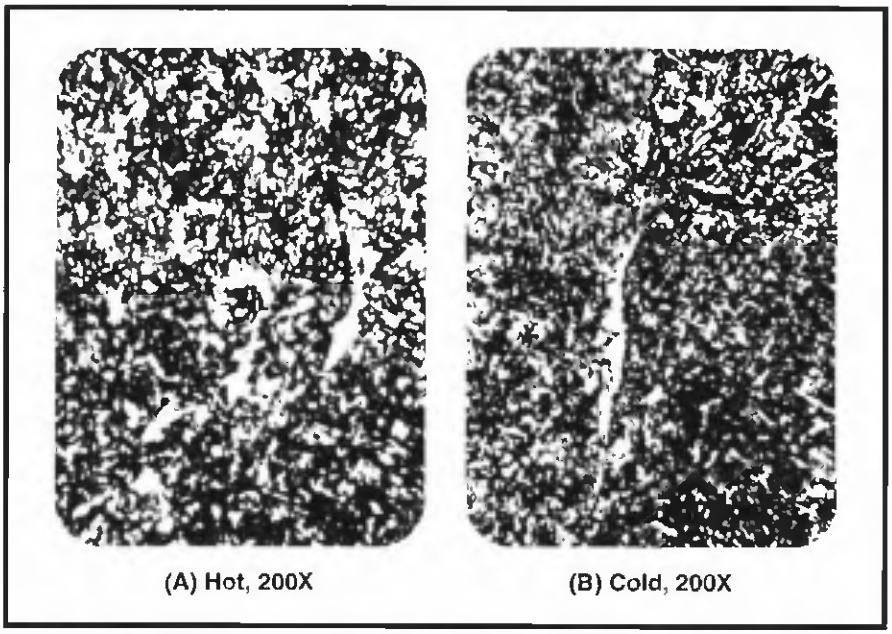

Fig. 2 — Photomicrographs of columnar zones (E12018-M): A — Hot 200X; B — Cold 200X.

Tensile Results

The tensile test data obtained for the six test assemblies, as well as the AWS requirements for each electrode, are presented in Table 7.

It generally can be observed that as the heat input increased, the tensile and yield strengths decreased, as previously found for E11018-M electrode (Ref. 1) and for similar high strength weld-metal obtained with different welding processes (Refs. 12, 17–20). With both electrodes and all the heat inputs, minimal elongation requirements were satisfied.

1) *E10018-M electrode:* with the three heat inputs, the obtained values of tensile properties were within the requirements of the AWS standard. Although the tensile properties varied according to the heat input that was used, this variation remained within the requirements of the AWS standard.

2) *E12018-M electrode:* only the medium specimen satisfied the AWS requirements. The cold specimen presented

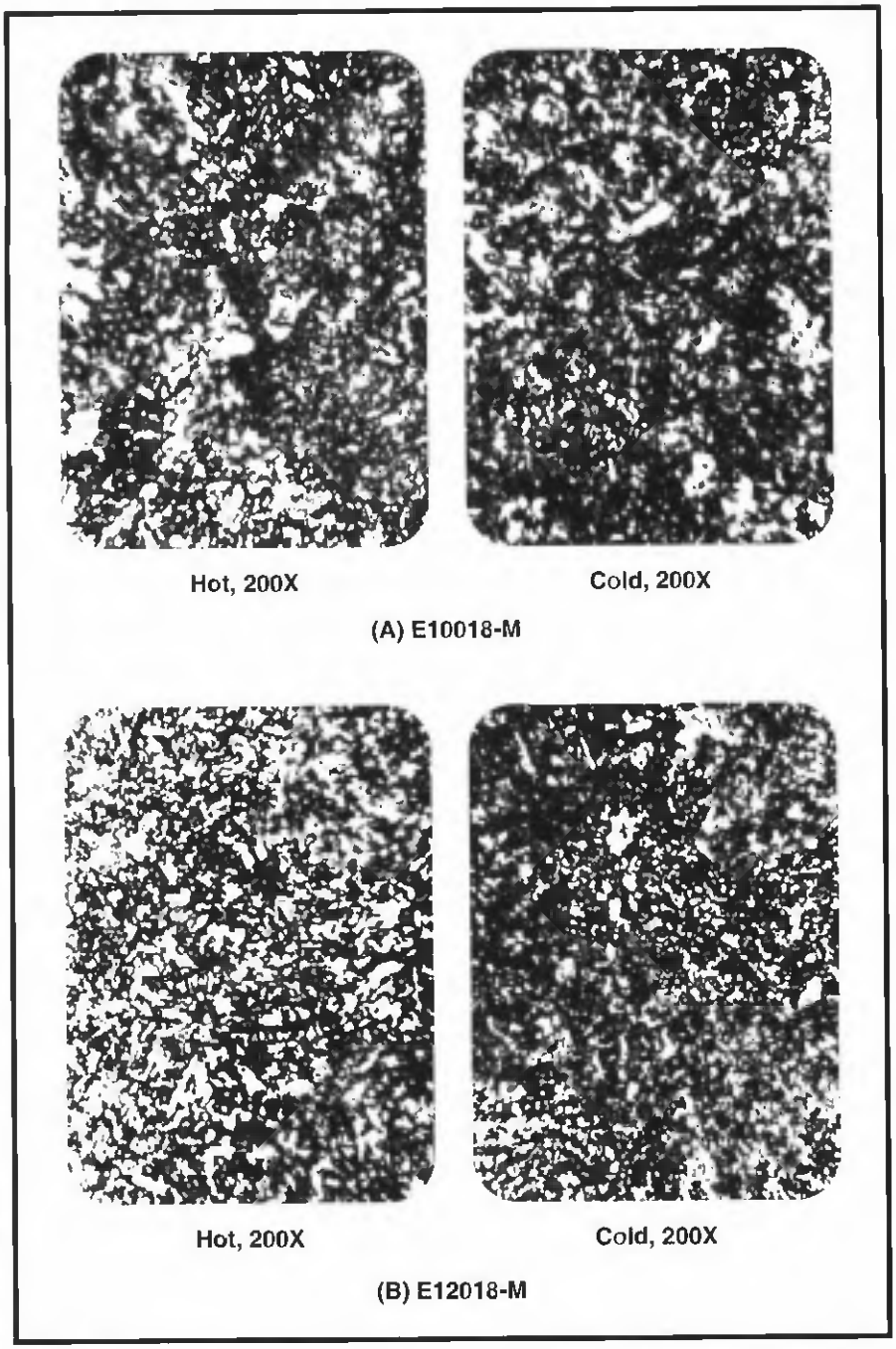

Fig. 3 — Photomicrographs of recrystallized zones: A — E10018-M, 200X; B — E12018-M, 200X.

yield strength that exceeded the maximum allowed and the hot one did not fulfill the minimal tensile strength required.

Impact Results

The Charpy-V impact values from the six test specimens are presented in Table 7. Values comfortably in excess of the minimum requirements were achieved with all the assemblies and there was not one value below the AWS minimal requirement. The average values were similar to those obtained with commercial E10018/ E11018/ E12018-M type electrodes (Refs. 21, 22).

The difference in the all-weld metal oxygen contents obtained with E10018-M and E12018-M electrodes could have been reflected in a toughness increase for the second electrode, as it is recognized that oxygen content affects the distribution (Ref. 23) and quantity (Refs. 24, 25) of inclusions: lower oxygen concentrations result in smaller inclusion diameter and lower volume fraction. These last two facts, in turn, result in better toughness (Ref. 26). In the present case, the beneficial lower oxygen content of E12018-M deposits may have been counteracted by the increase in tensile properties known to be deleterious to toughness (Ref. 27).

Discussion

It is well known that mechanical properties of low-alloy high-strength steel welds depend on their microstructure as well as on their chemical composition. Therefore, the rate at which welds cool and transform from austenite following solidification exerts a strong influence on their properties. In turn, cooling rate is dependent upon the conditions of welding. (Refs. 12, 17–20, 28–30).

The results presented in Section 3 showed, as expected, the variation of heat input produced changes in the all-weld-metal microstructure and mechanical properties.

In spite of the variations obtained in the mechanical properties, all the test specimens produced from the E10018-M electrode satisfied the AWS requirements, regardless of the value of heat input used, at least within the range employed in this work (1.3 to 2.1 KJ/mm) — Fig. 5. Therefore, with this electrode, it is possible to weld with a current varying from 140 to 185 A without the risk of not satisfying the requirements, according to Fig. 6. Thus, the versatility of this electrode is excellent.

With the E12018-M electrode, the situation is somewhat different. Figure 5 shows that the tolerance to heat input variations is smaller than the range employed in this work: no higher than 0.3 KJ/mm. The maximum heat input variation for E11018-M electrode, from Ref. 1, was 0.4 KJ/mm. This means that the admissible current variation for the electrode to satisfy the AWS requirements, would be approximately 15 A; see Fig. 6 (for E11018-M, 20 A was found—Ref. 1). This is a very demanding condition when one considers the variations usually found in the equipment calibration. The manufacturer would find it necessary to specify the exact parameters to be used with each different batch of electrodes, due to the expected unavoidable alloy variation that is obtained with the same formula. These changes in weld metal composition depend on the characteristics of the production facilities, how stringent the raw material specifications are, the quality system employed, etc. It can be seen that the current tolerance leading to tensile results within the AWS standard is large enough for the E10018-M. On the other

hand, the situation for the E11018/12018-M is completely different. Required tensile properties are only obtained within a very narrow heat input range.

Figure 6 points to still another fact: the ratio between the yield strength and tensile strength (YS/TS) increased from E10018-M to E12018-M. Typically, for

E10018-M	it is	0.87;
E11018-M	it is	0.93;
E12018-M	it is	0.96.

So, as the tensile strength rises, there is a smaller range in which to vary the heat input.

It was found in Ref. 2, that as Mn increased, the difference between yield strength and tensile strength decreased. On the other hand, in Ref. 3, where the tensile properties were increased by adding C instead of Mn, that difference was approximately constant or slightly lower. From Ref. 4, it can be seen that the addition of Cr did not alter the difference between YS and TS for all the Cr values considered. When Mn increased from nominal 1.0% to 1.5%, this difference was reduced, but it remained constant again for all the Cr levels for the same Mn content. The main difference between the chemical composition of deposits made from E10018-M and E12018-M electrodes is the addition of Cr, but there is also a small increase in Mn and Ni. This suggests that the overall increase of alloy content — not CR — is the cause for the convergence of yield and tensile strengths in the case under study.

Table 8 shows the percentage of variation of yield strength with respect to the mean value of the yield strength range required by AWS standard for the three electrodes. It can be observed that as the yield strength increases, the percentage of variation decreases, thus rendering the

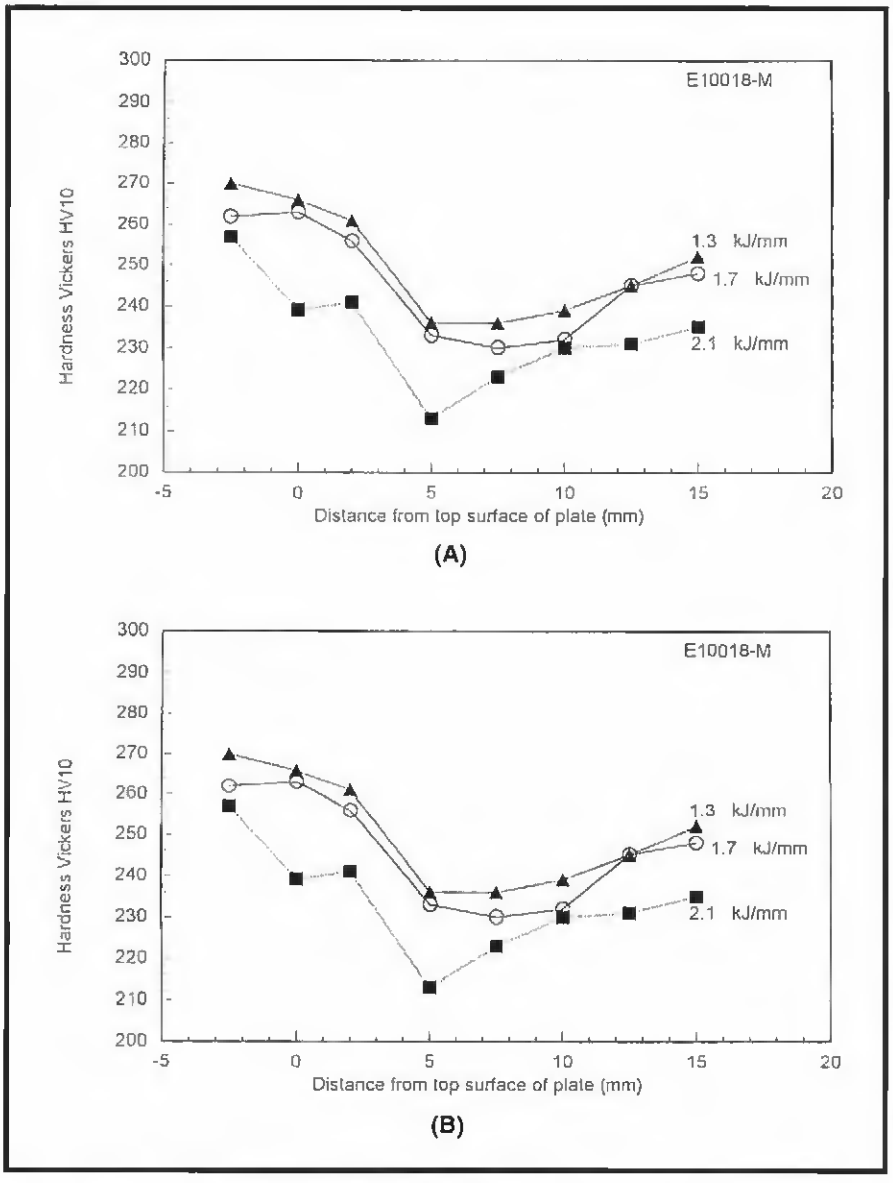

Fig. 4 — All-weld-metal hardness values: A — E10018-M; B — E12018-M.

Table 7 — All-Weld-Metal Mechanical Properties

	Heat Input KJ/mm	Condition	Tensile Strength (N/mm^2)	Yield Strength (N/mm^2)	Elongation (%)	Charpy V-Notch at –51°C (J)	
						Obtained Values	AWS Average
	2.1	Hot	724	632	23.4	54-57-50-54-56	55
E10018-M	1.7	Medium	760	660	22.8	57-58-55-56-54	56
	1.3	Cold	766	665	22.0	62-86-72-77-69	73
AWS requirements			690 min	610–690	20 min		27 min
	2.2	Hot	736–732	669–669	22.8–23.4	49-54-60-54-58	55
E11018-M	2.0	Medium	764–764	724–705	24.2–23.0	65-58-57-72-48	60
(Ref. 1)	1.6	Cold	811–809	774–766	20.3–22.8	31-51-53-36-47	45
AWS requirements			760 min	680–760	20 min		27 min
	2.1	Hot	796	754	20.7	57-44-65-53-56	55
E12018-M	1.6	Medium	845	814	19.7	35-62-50-39-66	50
	1.2	Cold	895	866	19.0	50-55-56-50-62	54
AWS requirements			830 min	745–830	18 min		27 min

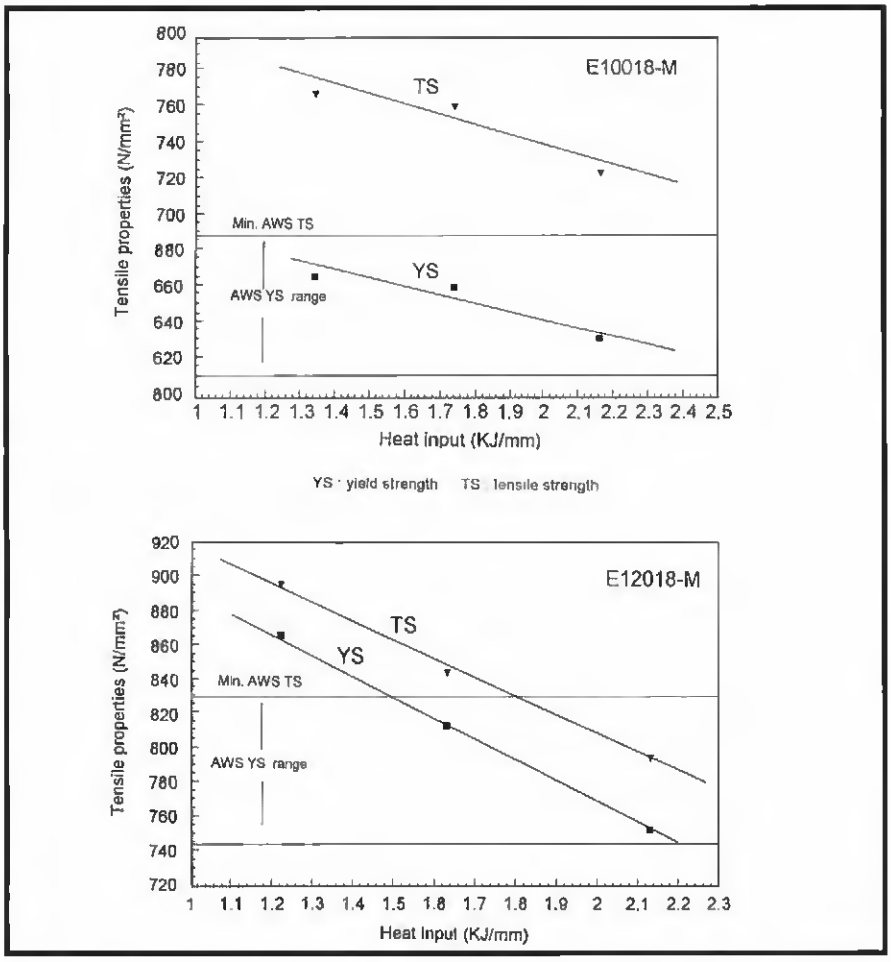

Fig. 5 — Tensile properties vs. heat input.

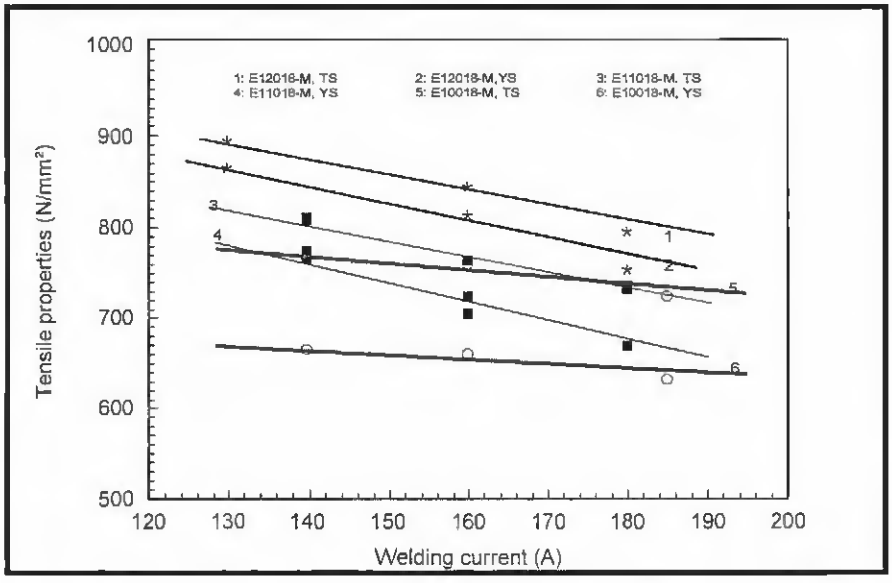

Fig. 6 — Tensile properties vs. amperage.

standard more demanding.

All these results show that in moving from E10018-M to 11018-M to 12018-M electrodes, weld metal is more sensitive to the variations of heat input, and this leads to a more stringent requirement on monitoring welding parameters in order to obtain the desired mechanical properties. These considerations are not only relevant to prepare the all-weld metal test specimens but also for the production batch testing of electrodes. The most risky situation is production welding because a strict procedure is necessary to ensure the reproducibility of results, which is not always possible to achieve.

Conclusions

With standard production E10018-M and 12018-M 4.0-mm diameter electrodes, three test assemblies were made according to the specifications of AWS AS.S-81, each with different heat inputs (high, low, intermediate). The following conclusions were found:

Tensile Properties

- E10018-M electrode — The three test specimens satisfied the AWS requirements, although the tensile properties varied with the three heat inputs.
- E12018-M electrode — Only the medium heat input specimen satisfied the AWS requirements, as happened with E11018-M electrode (Ref. 1). The cold specimen presented values of yield strength that exceeded the maximum required, and the hot one showed tensile strength that did not reach the minimum specified values.
- Minimal elongation requirements were fulfilled with both electrodes with the three heat inputs.

Charpy V-Notch Impact Toughness

- All the test specimens satisfied the AWS requirements; no individual value was below the requirements.

Metallography

- A decrease in the proportion of the columnar zones (and consequently an increase of the reheated zone) and an increase in the ferrite grain size were both found as the heat input increased. A small increase in both acicular ferrite and ferrite with second phase, at the expense of the primary ferrite, in the columnar zone, was also observed.

Hardness

- With the increase of heat input, the hardness values decreased; the E12018-M electrode had the highest hardness, as expected.

We thus conclude that the AWS all-weld-metal test assemblies with E12018-M electrodes must be performed under strict control and with very precise heat input to obtain reproducible results that satisfy the AWS requirements. These facts must be considered when the procedure test coupons and production weldments are performed.

AWS A5.5-81 and ANSI/AWS A5.5-96

- This study was performed according to AWS A5.5-81 requirements. Chemical composition and mechanical properties requirements of the two versions of A5.5 standard are the same, but the designs of the Groove Weld Test Assembly for Mechanical Properties and Soundness of Weld Metal are slightly different. This difference may account for variations in tensile properties results. In the opinion of the authors, the all-weld metal behavior general tendency will be the same if the new design is used to evaluate the variation of tensile properties with heat input, but this cannot be assured without the performance of adequate tests.

Acknowledgments

The authors wish to thank Conarco Alambres y Soldaduras SA for their permission to carry out this work, Eng. J. Sosa, Metallurgist of R&D, Conarco SA, for the metallographic study, Ms. Daniela Mayoral for editing this paper and Ms. María del Carmen Petrucelli for her permanent assistance in the performance of this work. Special thanks is given to Eng. Luis de Vedia for his invaluable help.

Table 8 — Percentages of Variation of Yield Strength with Respect to the Medium Value of the Yield Strength Range Required by AWS Standard for the Three Electrodes

Electrode	AWS Yield Strength Required Range (N/mm^2)	Yield Strength Required Range Medium Value (N/mm^2)	Yield Strength Range (N/mm^2)	% Yield Strength (from Medium Value)
E10018-M	610–690	650	80	±6.2
E11018-M	680–760	720	80	±5.6
E12018-M	745–830	787.5	85	±5.4

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