The Effect of Welding Parameters on High-Strength SMAW All-Weld-Metal — Part 1: AWS E11018-M

The influence of welding parameters on tensile strength of E11018-M electrodes welded to AWS A5.5-81 requirements was investigated

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ABSTRACT. Three AWS A5.5-81 all-weld-metal test assemblies were welded with an E11018-M electrode from a standard production batch, varying the welding parameters in such a way as to obtain three energy inputs: 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, and it was found that only the tensile properties obtained with the test specimen made with the intermediate energy input satisfied the AWS E11018-M requirements. With the "cold" specimen, the maximal yield strength was exceeded, and with the "hot" one, neither the yield nor the tensile minimum strengths were achieved. The elongation and the impact properties were high enough to fulfill the minimal requirements, but the best Charpy-V notch values were obtained with the intermediate energy input. Metallographic studies showed that as the energy input increased the percentage of the columnar zones decreased, the grain size became larger, and in the as-welded zone, there was a little increment of both acicular ferrite and ferrite with second phase, with a consequent decrease of primary ferrite. These results showed that this type of alloy is very sensitive to the welding parameters and that very precise instructions must be given to secure the desired tensile properties in the all-weld-metal test specimens and under actual working conditions.

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Introduction

To obtain good toughness with manual electrodes of the types E10018/11018/12018-M does not present many problems if a good formula achieves an adequate chemical composition. There are some papers (Refs. 1-3) that show it is possible to obtain optimum toughness with the carbon as low as possible (less than 0.05%), manganese between 1.0 and 1.4%, nickel 2.0% and molybdenum 0.30%, and that even with higher carbon (up to 0.10%) and manganese (up to 1.7%) and adding chromium up to 0.5%, it is possible to have good toughness values, which satisfy the AWS requirements of 27J minimum at -51°C (-59.8°F) (Ref. 4).

The question is how to get the adequate tensile properties, according to the AWS A.5.5-81 E11018-M requirements (Ref. 4) Table 1.

On some occasions, different values of tensile properties were obtained with the same batch of electrodes and the same welder; therefore, it was necessary to find the reason for these variations. The objective of this work was to study the influence of the welding parameters on the mechanical properties and microstructure when the test assembly is welded according to the AWS requirements (Ref. 4). The requirements of AWS A5.5-81 of two beads per layer and seven to nine layers for the joint establishes a range of usable heat inputs.

KEY WORDS

E11018-M
Weld Toughness
Charpy-V Notch
High-Strength Electrodes
Welding Parameters
Weld Tensile Strength
Heat Input
Microstructure

Experimental Procedures

Electrodes

Low-hydrogen iron powder E11018-M electrodes from a standard production were used. The core wire diameter was 4.0 mm (0.16 in.) and the coating factor (D/d) was 1.80. The electrodes were redried for 1 h at 350°C (662°F) before being used.

Weld Preparation

The weld geometry was that specified in AWS A5.5-81. Welding was performed in the flat position and two beads per layer were deposited as established by the mentioned standard.

The welding parameters and heat inputs employed for the three test assemblies are presented in Table 2. These parameters were chosen in order to weld with a high heat input and highest interpass temperature ("hot"), medium heat input and medium interpass temperature ("medium") and low heat input and the lowest temperature ("cold") possible to have good operational properties. The interpass temperature was maintained

Table 1 — AWS E11018 M Electrode Requirements

All-Weld-Metal Chemical Composition								
C	Mn	P	S	Si	Ni	Cr	Mo	V
0.10 max	1.30–1.80	0.030 max	0.030 max	0.60 max	1.25–2.50	0.40 max	0.25–0.50	0.050 max

All-Weld-Metal Mechanical Properties			
TS (MPa)	YS (MPa)	E %	Charpy-V at –51° C (J)
760 min	680–760	20 min	27 J min

Table 2 — Welding Parameters

Condition	Hot	Medium	Cold	AWS
Heat input (kJ/mm)	2.24	2.00	1.64	—
Amperage (A)	180	160	140	—
Arc Voltage (V)	25	24	23	—
Interpass T (°C)	107	101	93	93–107
Welding velocity (mm/s)	2.01	1.92	1.96	—
Number of layers	7	8	8	7–9

within the AWS A5.5-81 specified range (93°–107°C/199.4°–224.6°F).

Although not stated as such, the AWS A.5-81 standard contains a heat input limitation by requiring two passes per layer and limiting the number of layers from seven to nine.

Mechanical Testing

From each test assembly, two tensile specimens, one cut for metallographic studies, and five Charpy-V notch specimens were obtained. The tensile and toughness properties were tested in the as-welded condition at room temperature and at –51°C, respectively.

Metallography

Examinations of transverse sections were carried out on the top beads and the adjacent supercritically reheated zones, as described previously (Refs. 1–3) and according to Ref. 5.

Results

Chemical Composition

The chemical analysis of the three all-weld-metal deposits (six tensile specimens), as well as the one corresponding to the weld pad for chemical analyses, are presented in Table 3.

All the compositions satisfied the requirements of AWS A5.5.81 (Ref. 4) Table 1, and they were approximately within the optimum ranges for each element found in the mentioned previous studies (Refs. 1–3).

It can be seen that as the energy input increased, the values of Mn and Si decreased due to the higher oxidation of these two elements, which are not only alloying ones but deoxidizers, in the arc. This effect of the energy input was previously found by Evans (Refs. 6 and 7). Oxygen and nitrogen values decreased slightly with the decrease of the energy input. This was probably due to the fact that it was welded with lower arc voltage, and therefore a lesser quantity of these gases were in the arc environment (Refs. 8 and 9). Besides that, there was less time during which the weld pool could absorb O and N from the environment because it was smaller and solidified faster (Ref. 9).

The test specimen welded with the medium energy input presented an intermediate chemical composition very similar to that obtained with the weld pad, which was welded with the intermediate amperage.

Metallographic Examination

General

Table 4 presents the zonal distribution along the vertical centerline in the Charpy V-notch location for the three heat inputs employed. It is seen that as the energy input decreased the percentage of columnar zones increased. This occurred at the expense of the refined zones, as previously found (Refs. 6, 7).

As Deposited Weld Metal

Examination of as-deposited weld metal with low magnification revealed that the width of the prior/columnar austenite grains increased as the energy input increased. The measured values are presented in Table 5.

The last deposited beads were examined at 50 and 100X and quantitative metallographic measurements were performed at 500X, identifying the following major microstructural components:

1) primary ferrite.
2) acicular ferrite.
3) ferrite with second phase.

The point count results are given in Table 6. It is observed that as the energy input increased, the primary ferrite de-

Table 3 — All-Weld-Metal Chemical Composition

HI (KJ/mm)	C	Mn	P	S	Si	Ni	Cr	Mo	V	O ppm	N ppm
2.24	0.040	1.58	0.015	0.007	0.44	1.94	0.30	0.34	<0.010	361	84
Hot	0.040	1.57	0.015	0.007	0.44	1.94	0.30	0.32	<0.010	360	88
2.00	0.051	1.60	0.014	0.008	0.48	1.86	0.29	0.32	<0.010	321	84
Medium	0.043	1.63	0.016	0.007	0.48	1.97	0.31	0.35	<0.010		
1.64	0.040	1.67	0.016	0.007	0.54	1.92	0.30	0.34	<0.010	321	76
Cold	0.050	1.70	0.016	0.009	0.54	2.04	0.32	0.34	<0.010	309	67
Weld pad	0.05	1.61	0.017	0.010	0.50	1.95	0.30	0.34	<0.010		

creased and the acicular ferrite and ferrite with second phase increased. Typical microphotographs are shown in Fig. 1.

Reheated Weld Metal

It was not possible either to differentiate the coarse from the fine refined zones nor to measure the ferrite grain size because it was very small with this magnification, as can be seen in the photomicrographs presented in Fig. 2. It is noticeable, though, that the ferrite grain size generally decreased when the energy input decreased.

Mechanical Properties

Hardness Testing

Average hardness values obtained from the top and along the centerline of the test assembly are presented in Fig. 3, which shows that as the energy input increased the hardness values decreased. The fall of hardness values from the top to the bottom of the weld was more uniform as the energy input increased.

Soundness Test Results

The three test assemblies were radiographed in accordance with AWS A5.5-81 and presented optimum results: no apparent defects.

Tensile Tests

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

It can be observed that as the energy input increased, the tensile and yield strengths decreased, as previously found (Ref.6), but it is very interesting to see that with the cold specimen the maximum yield strength was exceeded, with the hot specimen the minimum yield and tensile strengths were not achieved and only with the intermediate energy input was it possible to satisfy the AWS requirements. But the three test assemblies were welded in accordance with the AWS standard (AWS A5.5-81 does not address welding parameters or heat input).

With the three welds the minimum elongation was obtained, and all the values were similar.

Impact Results

The Charpy-V notch impact values obtained for the different test assemblies are presented in Table 7.

Good impact values were obtained with the three welds: all of them were over the minimum required by AWS and the averages were normal values obtained with this type of electrode (Refs. 10–13). The best ones were those from the medium energy input, and the worst from the cold specimen, but actually all the values were very close and no scatter was present.

Discussion

Three test specimens were welded according to the AWS A5.5-81 standard using E11018-M manual electrodes from the same batch. The energy input was varied for each of them by increasing the amperage, voltage and interpass temperature, but always within the conditions (preheat interpass temperature, two passes per layer, seven to nine layers) fixed by the mentioned standard.

The metallographic examination of the three specimens showed an important increase in the percentage of the as-welded, columnar regions, at the expense of the recrystallized ones, at the Charpy-V-notch impact location, and a general and marked reduction of both prior austenite and ferrite grain sizes (in the columnar and refined zones, respectively) as the energy input diminished.

On the other hand, in the as-welded columnar zone, the decrease of the energy

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

Heat Input (KJ/mm)	Columnar Zone (%)	Refined Zone (%)
2.24	18	82
2.00	25	75
1.64	42	58

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

Heat Input (KJ/mm)	Width of Prior Austenite Grain (μ)
2.24	215.5
2.00	188.7
1.64	159.4

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

Heat input (KJ/mm)	AF (%)	FS (%)	PF (%)
2.24	74	20	6
2.00	72	19	9
1.64	66	17	17

AF: Acicular ferrite.
FS: Ferrite with second phases (carbides, retanied austenite) either aligned and non-aligned.
PF: Primary ferrite.

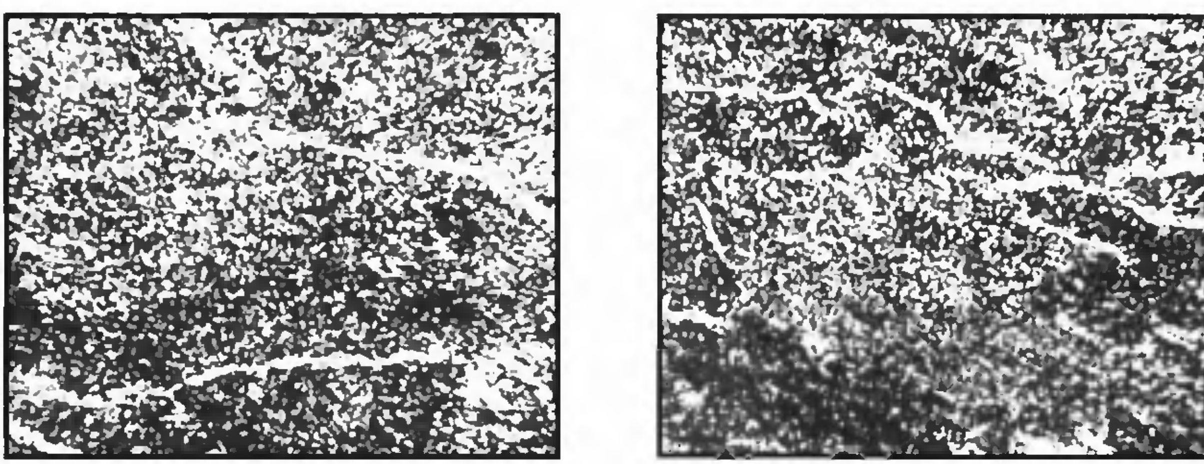

Fig. 1 — Photomicrographs of columnar zones. A — hot specimen; B — cold specimen.

Table 7 — Weld-Metal Mechanical Properties

Heat input (KJ/mm)	Condition		TS (N/mm²)	YS (N/mm²)	E (%)	Charpy-V at −51°C (J) Obtained values	Charpy-V at −51°C (J) AWS Average
2.24	hot	1	736	669	22.8	54-54-58	55
		2	732	669	23.4		
2.00	medium	1	764	724	24.2	65-58-57	60
		2	764	705	23.0		
1.64	cold	1	811	774	20.3	51-36-47	45
		2	809	766	22.8		
AWS requirements			760 min	680–760	20 min		27 min

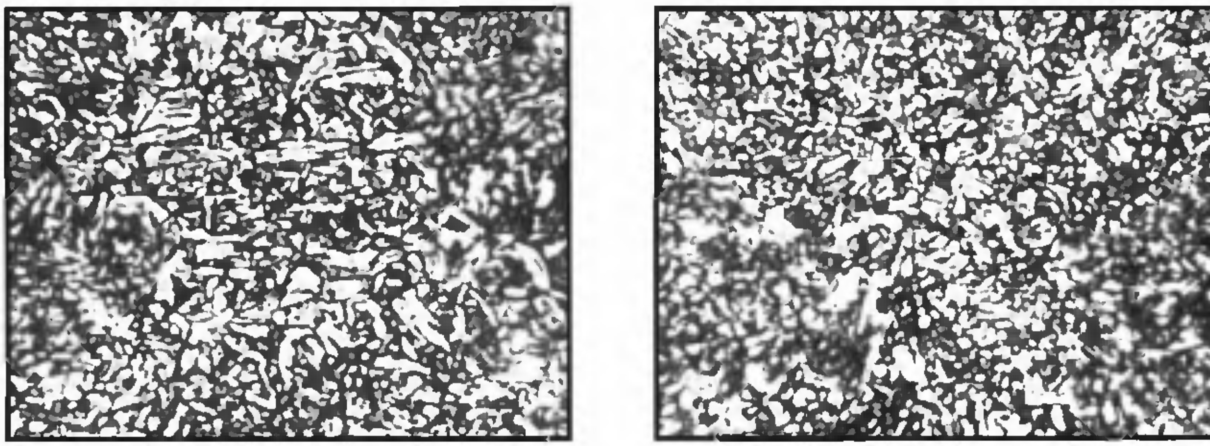

Fig. 2 — Photomicrographs of recrystallized zones. A — hot specimen; B — cold specimen.

input produced a slight decrease of both acicular ferrite and ferrite with second phase and an increase of primary ferrite.

As expected, the hardness values decreased with the increase of energy input. The "cold" specimen presented a pronounced wave distribution along the transversal cut of the all-weld-metal specimen, in which the peaks probably coincided with the columnar zones, as was previously found (Refs. 6, 7 and 14). When the percentage of the fine refined zones decreased with the energy input increase, the wave effect decreased and a very uniform fall of hardness from the top to the bottom of the weld was obtained ("hot" specimen).

The impact values obtained with the three energy inputs are very similar. The best ones are those from the medium energy input specimen. Taking into account the fact that better impacts are generally associated (among other effects) with: 1) grain size as small as possible; 2) higher percentages of recrystallized zones and 3) higher contents of acicular ferrite in the as-welded regions instead of primary ferrite and ferrite with second phase (Refs. 14–16), it would have been reasonable to expect the best toughness in the cold assembly because of effect 1, and in the hot assembly due to effects 2 and 3. It is possible that the medium as-

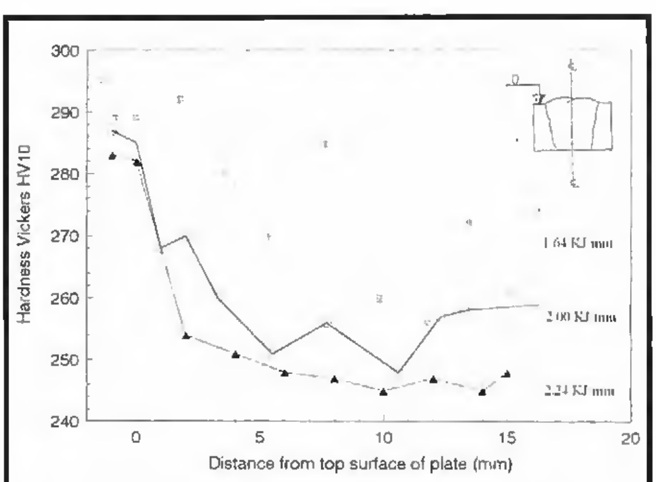

Fig. 3 — All-weld-metal hardness values.

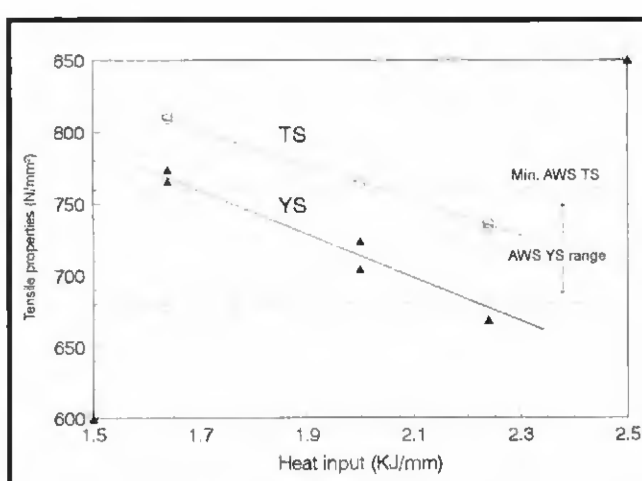

Fig. 4 — Tensile properties vs. heat input.

sembly presented the best combination of these three effects and because of that showed the best impact properties.

As the energy input increased, the tensile properties decreased as expected, due to the fact that some Mn and Si were lost through higher oxidation and that a general softening of the microstructure was developed, as exhibited by the decrease of the hardness values. But, in spite of the fact that the same electrode was used within the requirements of the AWS standard to weld the three test specimens, all the requirements were achieved only with the intermediate energy input. The all-weld-metal of the cold specimen exceeded the maximum value of the yield strength (760 N/mm^2) and with the hot specimen, neither the minimal yield (680 N/mm^2) nor the minimum tensile strength (760 N/mm^2) were achieved. The minimum elongation was satisfied with the three specimens.

Figures 4 and 5 show the tensile and yield strengths as a function of the energy input and the amperage, respectively, with the AWS tensile requirements indicated. It can be seen that changing the energy input through the welding current to obtain the required tensile values is possible and easy. But the complicated fact is that to be sure that the tensile values will always be obtained, it is necessary to have a smaller heat input range than 0.4 KJ/mm. If we accept that in this case the heat input is only a function of the amperage (because the variation of velocity and voltage were very low), the mentioned range would signify an amperage variation of 20 A. This value is within the normal variations that manual welding has, depending on the procedure, equipments, etc., and lower than the amperage range recommended by the manufacturers in their catalogs (Refs. 10–13).

It is important to call attention to the fact that the variation in yield strength obtained with this electrode between the hot and the cold specimens (about 100 N/mm^2) is bigger than the range specified (680 to 760 N/mm^2) by the AWS standard for this electrode. So, to guarantee that the tensile properties will be achieved with one batch of electrodes is difficult. Instead of an amperage range that usually appears in the producers' catalogs, more precise welding parameters must be given for each batch of electrodes due to the normal variations that the different productions present.

This simple experiment seems to show that the tensile properties of this type of all-weld metal are very dependent on the energy input variations, and consequently, to change the welding parameters in the appropriate way as to be always within the standard requirements is very easy. But this is a very dangerous situation because in manual welding there are always some variations due to equipment, personal characteristics of the welders, etc., that can influence the quality of the weld not only in the all-weld-metal test or the procedure test coupons but in the production weld.

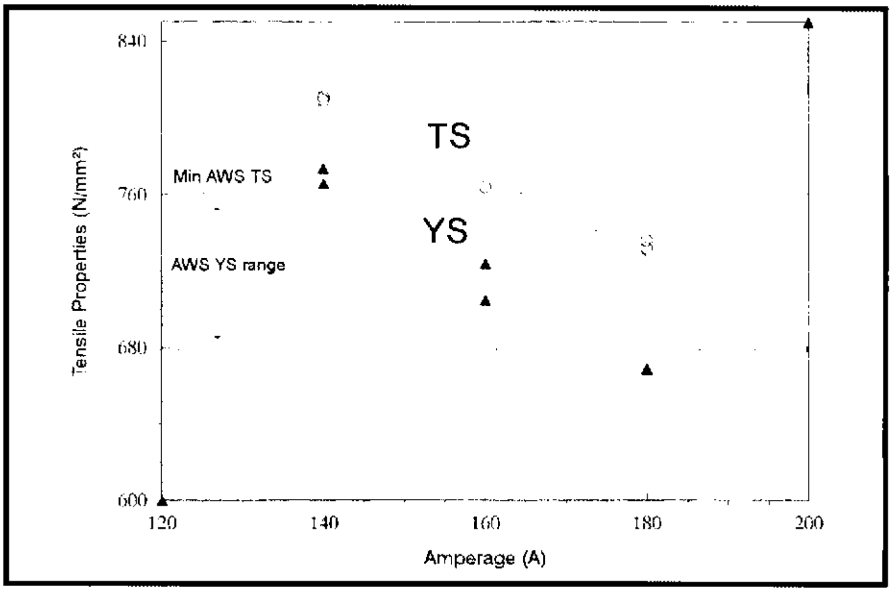

Fig. 5 — Tensile properties vs. amperages.

Conclusions

Using standard production 4-mm diameter E11018-M electrodes, three test assemblies were welded according to the specifications of AWS A5.5-81. Using different welding parameters, but all within the mentioned standard, high, intermediate and low energy inputs were obtained, which produced the following:

1) Three different values of tensile properties: the hot specimen produced less than the minimum tensile and yield strengths. The cold specimen exceeded the maximum yield strength. The medium specimen produced adequate tensile and yield strengths and elongation.

2) Good Charpy-V notch toughness values were produced in the three cases, with the medium heat input assembly being the best.

3) The percentage of the columnar zone decreased (and consequently an increase of the reheated zone occurred) and the grain size increased. In the columnar region, there were small increments of both the acicular ferrite and ferrite with second phases at the expense of the primary ferrite, as the energy input increased.

All these results show that a test assembly with this type of weld metal must be welded with special care and precise instructions, more than those presented in the AWS standard, to obtain repeatable results. Besides this fact, it seems very dangerous to have the possibility of manipulating the welding parameters, within the standard, so as to obtain the desired results. And even more than that, is the impossibility of controlling in such a precise way the use of the electrodes under actual working conditions.

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