The Effect of Magnesium Content on the Arc Stability of SMAW E7016-C2L/8016-C2 Covered Electrodes

Magnesium additions to the coating improved the charge and metal transfer during welding with alternating current

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ABSTRACT. The influence of magnesium powder additions to the coating of basic, low hydrogen AWS E7016-C2L/8016-C2 electrodes on the arc stability was studied, as well as the effects of the welding current type and the coating thickness. Overall, it was found that the magnesium content, the coating thickness and the welding current type affected the mechanisms of both metal transfer and electric charge transfer. It was concluded that magnesium additions to the coating, with alternating current (AC) welding, improved both the electric charge and the metal transfers. For direct current electrode positive (DCEP) welding, this effect appeared to be less significant. An increase in the coating thickness made both types of transfer difficult. Finally, with AC welding, for the same arc column length, the metal transfer became easier and the root mean square (rms) voltage value lower than for DCEP welding.

Introduction

The development of coated manual electrodes is fundamentally based on the adequate combination of different constituents of the coating (once the wire has been chosen) having such functions as to produce gas and slag protection and to add alloying metals, deoxidizers, arc starters and stabilizers, fabrication aids, and elements that improve the electrode performance. Because of that, formulating a coating is a very complex process that up to now has been based on the principle of trial and error. Nowadays, the trend researchers follow consists of looking for relationships among the coating constituents, the technological and economical characteristics of the electrodes and the deposited metal metallurgical properties to produce theoretical models for orientation of the experimental work.

One of the biggest challenges for electrode producers is to obtain welding consumables depositing high-strength metal with high low-temperature toughness. A typical example is the welding of steel with 3.5 wt-% nickel, used in the manufacture, storage and transport of liquids at low temperatures (propylene, carbon dioxide, acetylene, ethane, etc.). The AWS E7016-C2L-type electrode used for welding that steel requires a minimal tensile strength of 480 MPa and 27 J of absorbed energy in the Charpy V-notch test at −101°C. The secret for obtaining these properties resides in the selection of the electrode coating formula, that is to say, the combination of the coating raw materials, especially those combinations related to the deoxidizing system, which will produce a determined weld metal oxygen level, one of the controlling factors for the microstructure of the deposited metal. It is known that the use of traditional deoxidizers (Al, Ti, Si-Ti, Si-Zr, etc.) produces some transfer of these elements to the weld metal, which can decrease its toughness (Refs. 1–3). The best condition is to use a deoxidant that does not transfer itself to the weld metal.

Two previous experiences showed that metallic magnesium could be added to the electrode coating as a deoxidant without being transferred to the weld metal (Refs. 4, 5). These investigations showed that magnesium in the indicated quantities acts on the deposited metal oxygen content without producing significant changes in the rest of the chemical composition. Despite the lack of information about magnesium influences on the operational behavior of the electrode and its economical characteristics, it is known that magnesium modifies the slag properties (especially viscosity and basicity). It is necessary to evaluate the consequences of the use of magnesium on the performance of the electrode, with the arc behavior being one of the most relevant operational characteristics of the manual electrode process.

Arc Behavior

When welding with alternating current (AC), the current approaches zero in a certain interval of the cycle during which it is maintained by the effect of thermoionic emission (Ref. 8).

The emission capacity of the electrode when the cathode is formed, during the change of polarity, plays a fundamental role in the arc restriking and depends on both the electrode temperature and work function. However, in some cases, the work function under a slag is lower than that under an arc, resulting in low arc stability (Ref. 6). Then, other factors must be taken into account. Pokhodnya, *et al.* (Ref. 6), generalized the controlling factors of the arc restrik-

KEY WORDS

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Slag Composition
Metal Transfer
Charge Transfer
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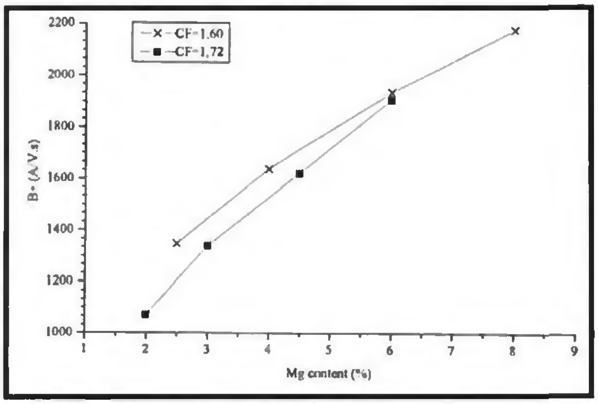

Fig. 1 — Effect of coating magnesium content on the ease of AC electric charge transfer.

ing process during the instantaneous polarity change to be as follows:

A) The temperatures of the electrode, weld pool and gas present in the arc column.

B) The composition of the gases present in the arc column.

C) The emission capacities of both the electrode and the weld pool.

D) The intensity of the electric field applied to the arc column.

Farias and Dutra (Ref. 7) also reported the important effect that the power source has on arc stability. They showed that, for a square wave power source, B and C above are less important. This observation happens because, as opposed to what occurs with conventional sine wave power sources, there is no reduction of the current in the instant polarity transition during this significant interval.

Besides, in the square wave sources the available voltage for the arc reignition (imposed by the source) acts during a very short time. In this case, the action of the source is more important than the actions of both the arc column composition and the electrode emission characteristics.

When welding with direct current (DC), arc extinction takes place during metal transfer for the short circuit transfer mode. During the short circuit, the current remains high and is even able to reach the double of the welding current for electromagnetic controlled power sources. Then, the most important factors acting on the arc restriking are the electrode and the weld pool temperatures. It is believed that, in this case, the other factors do not significantly affect the arc restriking mechanism because the high short circuit currents are enough to guarantee the ionization and subsequent arc restriking.

Other operational characteristics, such as the bead geometry, the slag detachability and the effect of the cone (cannon effect), are also important and must be analyzed. The cannon effect is characterized by the formation of a cone at the electrode tip (that is to say near the arc). This cone provides better arc protection and directs the molten metal to the weld pool. On the other hand, the cannon effect makes successive arc restriking difficult.

Bearing these ideas in mind, eight manual electrodes with variations in magnesium coating content and two different values for the coating factor (CF) = D/d (coating diameter-wire diameter) were investigated. With these electrodes the following working plan was designed: to study in detail the effect of the coating magnesium content on the all-weld-metal microstructure and mechanical properties, the economical characteristics, the performance of the electrodes and the arc behavior. In this paper, the results of the arc behavior with direct current electrode positive and with alternating current are presented.

Experimental Procedure

Electrodes

Four covered basic AWS E7016-C2L/8016-C2 type electrodes, 5 mm in diameter, with different levels of metallic magnesium additions to the coating, were investigated. These electrodes, which are presented in Table 1, were produced with two coating factors, CF = D/d (coating diameter-wire diameter). Each magnesium content alteration was compensated for with Fe-powder changes. On the other hand, as magnesium coating content increased, it was necessary to decrease manganese and Fe-Si (40 wt-%)

Table 1 — Coating Composition of Experimental Electrodes

	Coating composition (wt-%)					
Type of Electrode	Mg	Fe	Mn	Fe-Si	Ni	Coating factor
A	2.4	3.3	1.5	6.5	9.4	1.60
B	3.9	2.7	1.3	5.8	9.4	1.60
C	5.8	1.2	1.1	5.6	9.4	1.60
D	7.7	0.0	1.0	5.0	9.4	1.60
E	1.9	6.2	1.4	6.2	7.4	1.72
F	3.1	5.8	1.1	5.7	7.4	1.72
G	4.6	4.9	0.9	5.3	7.4	1.72
H	6.1	3.9	0.8	4.9	7.4	1.72

Table 2 — Weld Metal Chemical Composition on AC Welding (wt-%)

	Type of Electrode							
Element	A	B	C	D	E	F	G	H
C	0.070	0.074	0.086	0.104	0.066	0.074	0.082	0.097
Mn	0.78	0.71	0.60	0.69	0.76	0.70	0.68	0.65
Si	0.40	0.33	0.34	0.32	0.39	0.41	0.38	0.35
P	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
S	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
Ni	3.53	3.44	3.42	3.37	3.36	3.47	3.27	3.07

Obs: Mg, V, Al, W, Mo <0.01
Ti = 0.02 Co, Nb = 0.01
Cu = 0.06–0.08 Cr = 0.01–0.04

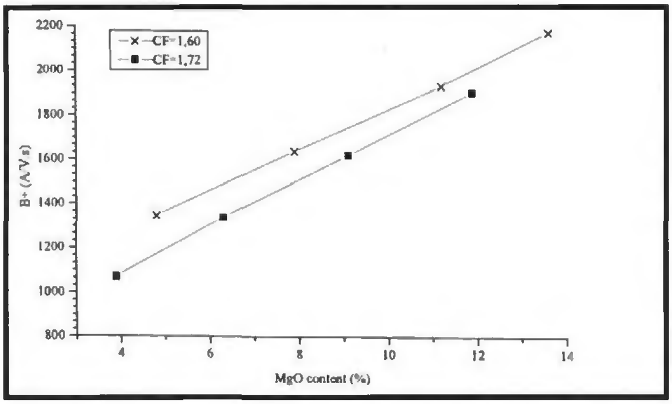

Fig. 2 — Effect of MgO content of the slag on the ease of AC electric charge transfer.

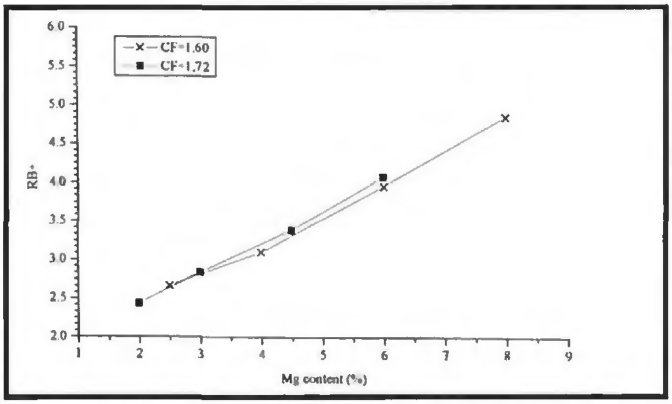

Fig. 3 — Effect of coating magnesium content on the regularity of the AC electric charge transfer.

coating powders due to the deoxidant role of magnesium, because the investigation was designed not to incorporate another variable but to obtain approximately the same all-weld-metal alloy (Table 2). The total amount (% in weight of coating) of the mineral constituents (76.9 wt-%) was maintained constant in all the electrodes, as described below.

1% SiO_2, 16% CaF_2, 9% TiO_2, 1.4% K_2O, 1.0% Na_2O, 2.5% Zr_2O, 46% $CaCO_3$.

Table 3 presents the slag chemical composition of the electrodes. It can be observed that with the increase of magnesium in the coating, the slag MgO content increased and the MnO and SiO_2 contents decreased, as expected.

Weldments

With the electrodes described above, bead-on-plate weldments in the flat position were made on 50 x 200 x 10 mm ASTM A-36 plates with both DCEP and AC. An electromagnetic, 300-A, constant current power supply (sine wave rectifier) was used.

Arc Stability Measurements

Data was compiled with the assistance of a computer-aided data acquisition system of programmable frequencies up to 12 kHz in each channel (voltage and current). Each experimentwas repeated four times using the welding parameters that appear in Table 4.

The instantaneous values of arc voltage and current were recorded at 11 kHz (with 12-bit resolution) for 5 s, totaling 20 s of acquisition for each type of electrode and current. All the variables determined with both DCEP and AC, as well as those quantities employed in the following equations, are listed and defined in the Appendix.

It can be seen in the literature (Refs. 6, 8) that the term "arc stability" is widely used, but there is no consensus regarding its definition or its evaluation. In the majority of the cases, the arc stability evaluation considers the metal transfer and the electric charge transfer mechanisms separately. The authors believe that a stable arc has to achieve two basic requirements: easy and uniform metal transfer, as well as electric charge transfer. Based on this statement, it was proposed to follow the criterion that uses the instantaneous values of welding voltage and current to evaluate the arc stability, considering both the electric charge transfer and the metal transfer mechanisms (Ref. 8).

Electric Charge Transfer Mechanism

The ease of electric charge transfer was evaluated through the index FE_1 (Ref. 8) with DCEP and the index B^+ (Ref. 9) with AC.

$$FE_1 = \frac{1}{E_1} = \frac{2000}{(P_1 - P_0)\cdot t_1} \quad (W^{-1}s^{-1}) \qquad (1)$$

FE_1 is the inverse of the restriking mean energy after the short-circuit occurrence with DC welding. (E_1, P_1, P_0 and t_1 are defined in the Appendix.)

When welding with alternating current, during each new half-cycle, a particular time, t_1, passes before the power supplied to the electrodes attains a level required for the recovery of the arc discharge (Ref. 9). When U_1 and I_1 are, respectively, the voltage on the electrodes and the current in the interelectrode space at the moment of discharge recovery, the characteristic of stable arc burning, B, for the positive half-cycle, can be determined as (Ref. 9)

$$B^+ = \frac{I_1^+}{U_1^+ \cdot t_1^+}\cdot 1000 \qquad (\Omega^{-1}s^{-1}) \qquad (2)$$

B^+ is the mean speed of increase in electrical conductivity of the interelec-

Table 3 — Slag Chemical Composition on AC Welding (wt-%)

	Type of Electrode							
Type of Oxide	A	B	C	D	E	F	G	H
MnO	2.10	1.40	0.90	0.85	1.60	1.40	1.00	0.80
FeO	2.40	2.20	1.80	2.00	2.50	2.20	1.90	1.80
CaO	34.6	33.5	32.1	30.8	34.2	32.8	33.4	31.1
K_2O	2.00	2.00	1.70	1.30	2.30	2.00	2.00	1.50
CaF_2	16.0	16.2	16.8	16.6	18.0	18.1	16.5	17.3
MgO	**4.80**	**7.90**	**11.2**	**13.6**	**3.90**	**6.30**	**9.10**	**11.9**
Na_2O	1.80	2.30	2.40	1.80	2.40	2.20	1.60	1.90
TiO_2	12.0	11.5	11.2	10.8	11.7	11.5	11.5	11.0
Al_2O_3	0.60	0.50	0.50	0.50	0.50	0.50	0.60	0.50
Zr_2O_3	2.90	2.80	2.70	2.70	2.80	2.70	2.70	2.70
SiO_2	22.2	21.2	20.5	19.7	22.0	22.0	21.4	19.5
NiO	0.20	0.20	0.10	0.10	0.30	0.20	0.10	0.10

trode space during the positive pre-arc period. (I_1^+, U_1^+ and t_1^+ are defined in the Appendix.)

The regularity of the electric charge transfer was also evaluated by means of the indexes RE_1 with DCEP and RB^+ with AC. They represent the inverse of the relative root-mean-square deviations of the indexes E_1 and B^+.

$$RE_1 - \frac{E_1}{\sigma_{E_1}} \qquad (3)$$

$$RB^+ = \frac{B^+}{\sigma_{B^+}} \qquad (4)$$

Metal Transfer Mechanism

In this case, the ease of the metal transfer was evaluated through the indexes F_{cc} and F_{tm}. They represent the ease of short-circuit occurrence and the ease of drop transfer in the short circuit transition mode, respectively.

$$F_{cc} = \frac{1}{T} \quad (s^{-1}) \qquad (5)$$

$$F_{tm} = \frac{1}{t_{sc}} \quad (s^{-1}) \qquad (6)$$

The consistency of metal transfer was evaluated through the indexes R_{cc} and R_{tm}. They represent the inverse of the relative root-mean-square deviation of the short circuit period (T) and of the short circuit time (t_{sc}), respectively.

Table 4 — Welding Parameters

Type of Current	Irms (A)	Urms (V)	Vs (mm/s)
DCEP	200	25–26	2.5
AC	200	22–24	2.5

$$R_{cc} = \frac{T}{\sigma_T} \qquad (7)$$

$$R_{tm} = \frac{t_{sc}}{\sigma_{t_{sc}}} \qquad (8)$$

All the dependent variables were submitted to a variance analysis (Ref. 10) with a confidence level of 95%, for determination of the significance level (α) of the analyzed effects. As the variation of the chemical composition differed for each coating factor, these analyses were done separately. With the exception of the figures related to the electric charge transfer with AC, the rest of the analyses refers to the process with metallic transfer, that is to say, that only short-circuits with larger duration than 2.0 ms were considered, because they actually transfer the metallic drop (Ref. 8).

Results and Discussion

Electric Charge Transfer with AC Welding

The analysis of Fig. 1 indicates that the addition of magnesium to the coating increased the ease of electric charge transfer, measured with index B^+, but the coating factor did not seem to have any notable effect. The magnesium could play a similar role as described by Pokhodnya, *et al.* (Ref. 9), for titanium. These elements, with high affinity for oxygen, oxidize themselves intensively and are transferred to the slag as oxides, increasing the slag thermoionic capacity. These oxides have a low work function and the slag containing them would have its work function reduced. Figure 2 shows that the ease of the charge transfer increased with the increment of slag MgO content (that is to say with the slag magnesium content increment, Table 3). Furthermore, to make the reignition of the arc easier, the magnesium improved the consistency of the electric charge transfer, as is indicated in Fig. 3, independent of the coating factor.

Electric Charge Transfer with DC Welding

Under normal welding conditions, with DCEP, the arc extinction takes place at the short circuit, during which the current remains high and as much as twice the welding current, depending on the type of power source. This behavior produces high temperatures in the electrode tip and the weld pool, thus facilitating the arc reignition process after the drop has been transferred. It is believed that, in this case, the slag chemical composition (Table 3) does not affect the arc restriking mechanism because the high short circuit currents are enough to guarantee the ionization and subsequent arc restriking. The analysis of Fig. 4, checked by the variance analysis, indicated that the magnesium did not influence the ease of the charge transfer with DCEP. However, the effect of the coating thickness appeared to be more important with DCEP than with AC. The coating factor increment (from 1.60 to 1.72) made the electric charge transfer with DCEP more difficult. The electrodes with a higher coating factor, presented higher arc power peaks at the instant of reignition, as a result of higher voltage peaks. It was observed that there was an augmentation of the "cannon effect" with the rise of the coating factor. In this way, it is considered that the coating factor rise proportionally elevated the quantity of gases to be ionized. This result can explain the higher power peaks of the electrodes with CF = 1.72 with DCEP. The regularity of the charge transfer was independent of the magnesium content and the coating factor with DCEP, as is indicated in the statistical texts and illustrated in Fig. 5.

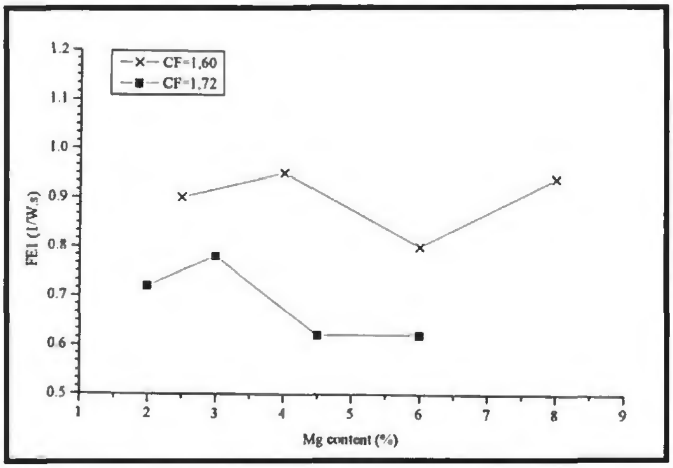

Fig. 4 — Effect of coating magnesium content on the facility of the electric charge transfer with DCEP.

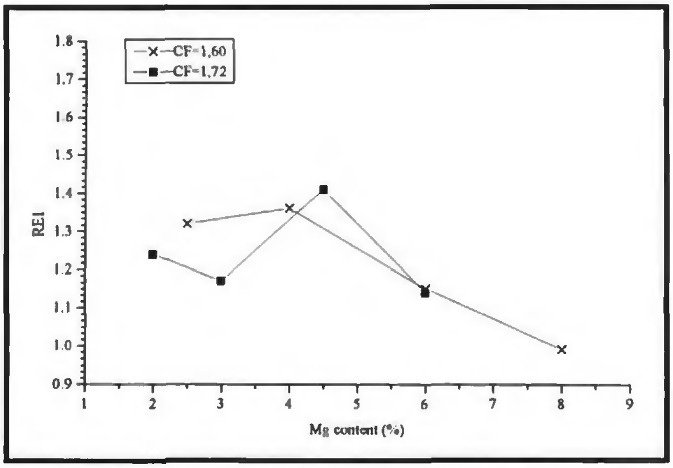

Fig. 5 — Effect of coating magnesium content on the regularity of the electric charge transfer with DCEP.

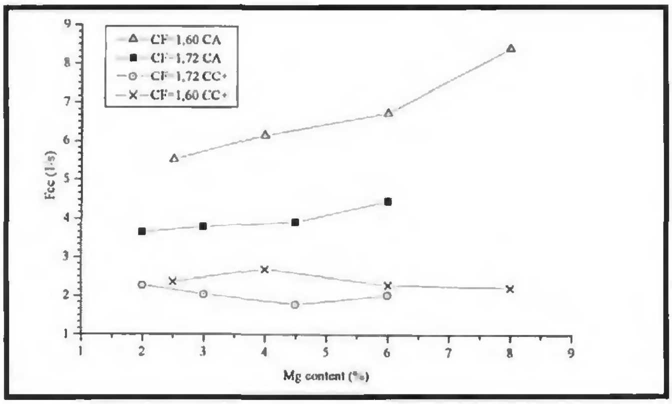

Fig. 6 — Effect of coating magnesium content on the short circuit frequency.

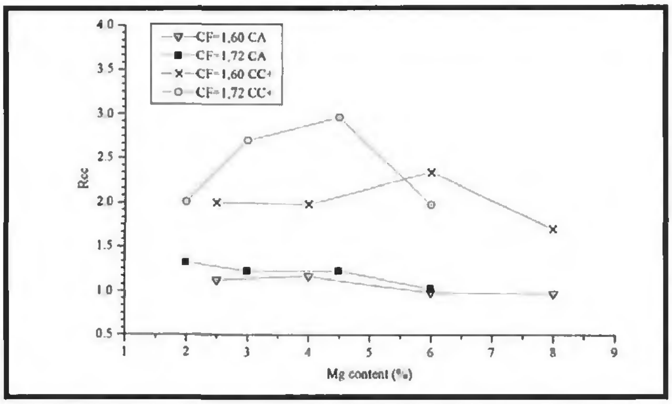

Fig. 7 — Effect of coating magnesium content on the regularity of short circuit occurrence.

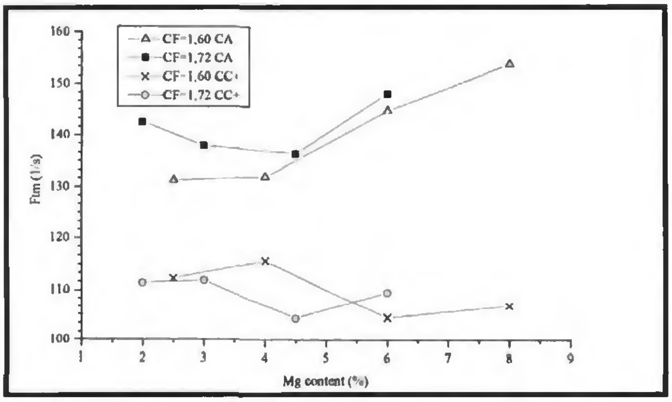

Fig. 8 — Effect of coating magnesium content on the ease of metal transfer.

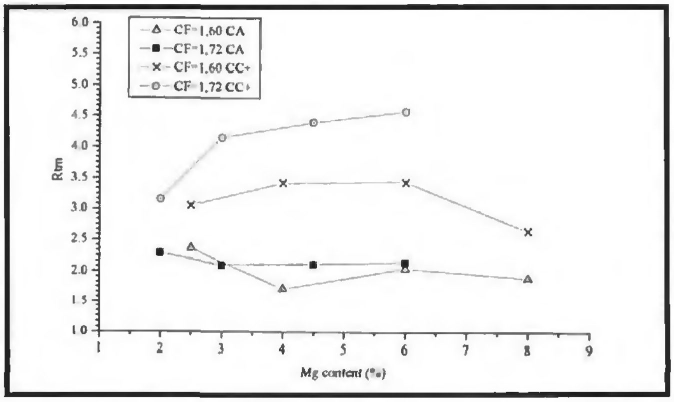

Fig. 9 — Effect of coating magnesium content on the regularity of metal transfer.

Metal Transfer

The slag composition variations can affect both the slag and liquid metal properties. However, for the analyzed values, magnesium additions did not produce enough alterations in these properties to influence the metal transfer mechanism. According to Figs. 6–9 and the analysis of variance, it can be seen that magnesium additions to the coating did not modify the metal transfer significantly. The most significant effect was the one produced by the current type. The ease of the metal transfer with AC, characterized by a larger ease of both the short circuit occurrence (Fig. 6) and the metal transfer (Fig. 8), was higher than with DCEP, but the regularity was greater with DCEP. The comparison between DCEP and AC welding results offered a complication that must be taken into account. It is not easy to obtain identical parameters on both currents with the same electrode. For the same arc length, the rms voltage depends on both the coating type and the current type. On the other hand, when the objective is to find identical rms voltages, different arc lengths are achieved. In this paper, the efforts were concentrated on maintaining a constant arc length as much as possible throughout the experiments. However, a difference in the actual arc length with the electrodes with two different coating factors was expected, due to the "cannon effect." The rms voltage was always lower for the finer electrode and with AC (Table 4). It is thought that the higher short circuit frequencly lowers the rms value with AC.

With DCEP, the coating factor had no effect on the metal transfer mechanism. In fact, with AC, the higher possibility of short circuit occurrence for a finer coating electrode could be reported — Fig. 6. According to Pokhodnya, *et al.* (Ref. 11), the increase in coating thickness of basic electrodes drastically decreases the short circuit time (increases the ease of metal transfer). Nevertheless, these results were not confirmed in this investigation. The augmentation of the coating factor slightly increased the ease of the metal transfer with AC, but did not produce a significant effect with DCEP — Fig. 8.

In spite of the fact that the ease of both short circuit occurrences and metal transfer improved with AC, they were less regular. This result means that with AC there is a higher variation of these values around their averages.

Final Considerations

The variation of the magnesium content in the coating was compensated with iron powder, manganese and Fe-Si, as indicated in Table 1. It is supposed that this fact did not alter the arc ionization potential, as a result of the similar values of ionization energy of iron (7.83 eV), magnesium (7.61 eV) and silicon (7.94 eV). Because manganese presents lower ionization energy (4.70 eV), it seems possible that its maximum variation of only 0.55 wt-% was not enough to influence the arc behavior. These facts can justify the absence of magnesium effect on the charge transfer with DCEP — Fig. 4. However, with AC, the arc electric conductivity during the polarity transition period depends on the emission properties of the slag. In this case, the magnesium played an important role due to its effect on the slag work function and, consequently, on the slag emission properties. For magnesium contents under 3 wt-%, the obtained values of arc stability (ease and consistency of the charge transfer with AC) were higher than those achieved with AWS E6013 rutile-type electrodes (Ref. 8). This result characterized the magnesium as an excellent arc stabilizer with AC. Besides, it had no significant effect on the metal transfer on either type of current. Meanwhile, a reduction of the slag viscosity was observed with the increment of electrode coating magnesium content. This viscosity reduction caused incomplete slag protection of the weld bead during its solidification. A more difficult slag detachability for Mg content higher than 6.0 wt-% was also observed. In spite of that, there was no significant influence of the magnesium content on the weld bead geometry.

This effect is in accordance with what is generally known from empirical results as regards the development of basic coated electrodes (for example, E7018 type). The E7018 coating, when the electrode is only for DCEP, does not need to have any other deoxidizer/stabilizer than silicon and manganese. But, if it is requested for AC, it is necessary to add an arc stabilizer, for example, titanium or aluminum. Unfortunately, these elements are partially transferred to the weld metal, and, above certain values, they are pernicious for toughness (Ref. 1–3). Then, it is probable that the use of magnesium in this type of electrode improves its performance with AC, without decreasing toughness as happens with E7016-type electrodes, which do need the addition of arc stabilizers because they are especially requested for AC.

A study with similar electrodes with AC (Ref. 4), concluded that the increase in magnesium content in the coating from 4 to 6 wt-% affected neither the microstructure nor the all-weld-metal tensile strength, but there was a reduction in the oxygen content (from 470 to 300 ppm), which affected the Charpy V-notch impact values directly (from 32 to 61 J at –101°C).

The results here presented refer to welding carried out with a specific power source. It is expected that the use of other constant current power sources can alter these results, because the arc stability depends on the static and dynamic characteristics of the power source.

Conclusions

The effect of magnesium content on the arc stability of E7016-C2L/8016-C2 covered electrodes was studied. On the basis of the present investigation, a methodology to evaluate the arc stability was proposed. The results indicated that the increase in coating magnesium content increased the ease and consistency of the charge transfer, measured through indexes B^+ and RB^+ with AC, but did not markedly affect the charge transfer with DCEP. On the other hand, the metal transfer was not significantly affected by magnesium additions.

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References

1. Evans, G. M. 1986. Effects of silicon on the microstructure and properties of C-Mn all-weld-metal deposits. *Metal Construction*, Vol. 18, July, pp. 438–444.

2. Evans, G. M. 1989. The effect of aluminium on the microstructure and properties of C-Mn all-weld-metal deposits. *IIW Doc. II-A791-89.*

3. Evans, G. M. 1991. The effect of titanium on the microstructure and properties of C-Mn all-weld-metal deposits. *IIW Doc. II-A827-91.*

4. Surian, E. S., Trotti, J. L., and Boniszewski, T. 1992. Effect of oxygen content on Charpy V-notch toughness in 3.0% Ni steel SMA weld metal. *Welding Journal*, 71(7): 263–268.

5. Abson, D. J., and Evans, G. M. 1989. A study of manganese-oxygen systems in low hydrogen MMA all-weld-metal deposits. *IIW Doc. II-A-770-89.*

6. Pokhodnya, I. K., Gorpenyuk, V. N., Milichenko, S. S., Ponomarev, V. E., Starodubtsev, L. V., and Shvachko, V. I. 1991. Welding arc stability. *Metallurgy of Arc Welding*. Vol. 1, Arc Processes and Electrode Melting. Chapter 2, Abington, Cambridge, U.K.

7. Farias, J. P., e Dutra, J. C. 1993. Estudo comparativo de diferentes fontes de energia na soldagem com eletrodos revestidos. *XIX Encontro Nacional de Tecnologia da Soldagem*. Águas de São Pedro, SP. Outubro de 1993.

8. Farias, J. P. 1993. Magnésio metálico como componente do revestimento na soldagem com eletrodos ao C-Mn-Ni. *Tese de Doutorado*. UFSC, Brazil, pp. 225.

9. Pokhodnya, I. K., Marchenko, A. E., Gorpenyuk, V. N., Makarenko, V. D., and Starodubtsev, L. V. 1980. Study of alternating current arc stability. *Arc Physics and Weld Pool Behaviour*. Vol. I, . The Welding Institute, Cambridge, U.K., pp. 93–99

10. Montgomery, D. C. 1984. Design and analysis of experiments. John Wiley & Sons. Canada.

11. Pokhodnya, I. K., Makarenko, V. D. Gorpenyuk, V. N., Ponomarev, V. E., Kasatkin, O. G., Taraborkin, L. A., and Milichenko, S. S. 1984. Research into the special features of metal transfer and arc running stability in welding using basic-coated electrodes. *Automatic Welding*, April, pp. 39–42.

Appendix: Definitions of Arc Variables

E_1 The restriking mean energy after the short-circuit occurrence with DC welding (W.s)

$$E_1 = \frac{(P_1 - P_0) \cdot t_1}{(2000)}$$

P_1 The restriking mean power after the short circuit (W)

$$P_1 = U_1 \cdot I_1$$

where U_1 is the restriking mean voltage (V), I_1 is the restriking mean current (A), and P_0 is the reference power (W)

$$P_0 = U_0 \cdot I_0$$

where U_0 is the reference voltage (U_0 = 10 V), I_0 the reference current (A) (the correspondent value of current in the beginning of the arc restriking), and t_1 the restriking mean time (ms)

Observation: The variable E1 represents the area over the dynamic behavior (P x t) of the arc power, during the arc restriking after the short-circuit occurrence, which was considered approximately as a triangle.

The variables determined with AC and with DC were:

I_{rms} The root-mean-square current (A).

U_{rms} The root-mean-square voltage (V).

T The short circuit period average (ms).

σT Root-mean-square deviation of T.

t_{sc} The short circuit time average (ms).

σt_{sc} The Root-mean-square deviation of t_{sc}.

The variables determined only with AC, at the polarity change for the positive half cycle, were:

U_1^+ The positive restriking mean voltage (V).

I_1^+ The positive restriking mean current (A).

t_1^+ The positive restriking mean time (ms).

σB The root-mean-square deviation of B^+.