The Effect of Wollastonite on Operational Characteristics of AWS E6013 Electrodes

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The main objective of this work was to assess the operational behavior of ANSI/AWS A5.1-91 E6013 type electrodes when 0, 8 and 16 % of quartz (100 % SiO_2) is replaced with wollastonite (Calcium Silicate, 50 % SiO_2 - 50 % CaO) in the coating composition. The electrodes were tested through bead-on-plate welds in flat position on DC, both polarities, and on AC currents. Arc stability, fusion rate and deposition rate were used as operational characteristics evaluation criteria. The results suggested that the replacement of quartz with wollastonite, that increased slag basicity, kept, or even improved, the typical excellent operational characteristics of E6013 type electrodes.
Keywords*: Wollastonite; covered electrodes; arc stability; basicity*

Introduction

During the 1980s, an important decrease in the usage of manual electrodes took place in the developed countries (Myazaki,1998; Svenson et al, 1999). Despite that fact, in Latin-America, almost 80% of the deposited weld metal comes from this type of welding consumables (Timerman and Vedia, 1991). In addition, accompanying the noticeable growth of steel production in China and India, a marked increase in manual electrode use was observed (Taylor,1990). Everything seems to indicate that the utilization of manual electrodes will stabilize in a 20-30% of the deposited weld metal (Myazaki,1998; Svenson et al, 1999), due to the following reasons (Taylor,1990), among others:

- Simplicity, durability and low cost of the required equipment.
- Possibility of being used in open and closed spaces.
- Wide range of consumables for most applications, which is a function of the quick set up fabrication.
- Availability in small units and at relatively low cost. It is generally accepted that welding consumables represent the 1-2 % of the final cost in general fabrication.
- Possibility of finding welders with the adequate skill for most of their applications, easily.

Another interesting matter is that rutile-coated electrodes of the type ANSI/AWS A5.1-91 E6013 and E7024 continue to be required in different markets. This is so to such a degree that, there were no Charpy requirements for ANSI/AWS E7024 Classification up to 1981. In ANSI/AWS A5.1-81 Specification (ANSI/AWS, 1981), a new variant identified as “E7024-1” was introduced for those E7024 electrodes which were required to deliver 27 J at -18ºC and the same is required in the latest ANSI/AWS A5.1-91 Specification (ANSI/AWS, 1991).

During the last 20 years a lot of work has been done in order to acquire more knowledge about electrodes depositing C-Mn steels. Much attention was concentrated on the study of manual basic coated electrodes of the types ANSI/AWS A5.1-91 E7018 (Evans, 1983, 1990) and E7016 (Taylor, 1982; Surian and Boniszewski, 1995), leaving aside those of the rutile type. As far as the authors are aware, only a few papers about E7024 (Surian et al, 1995) and E6013 (Rissone et al, 1995; Boniszewski et al, 1995; Boniszewski and Evans, 1995; Boniszewski and Evans, 1995; Boniszewski and Colvin, 1995; Rissone et al, 2002) type electrodes have been published in the last years with the aim of establishing the relationship between chemical composition, microstructure and mechanical properties of the deposited metal, as much as, the relationship between these properties and operational behavior. From the point of view of their operational properties, rutile electrodes are known as the best ones compared to cellulosic and basic ones.

The mentioned knowledge on rutile electrodes is becoming more important everyday due to the possibility of:

- using them in underwater wet welding, for which the basic ones are not the most adequate (Ibarra et al, 1989; Sanchez-Osio et al, 1993.);
- generating knowledge on rutile slag system, by using inexpensive material (covered electrode), that can be employed on the development of rutile flux wire for all positional welding;
- obtaining formulations capable of satisfying the Grade 3 requirement of the Unified Classification Societies (ABS, BV, DnV, LRS) for the navy industry (Charpy-V impact of 47 J at -20ºC) (Lloyd’s, 1994).

For these reasons, a joint research program has been initiated with manual coated electrodes of the AWS A5.1-91 E6013 type.

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The first step was to study the effect of varying the slag basicity through the increase of Calcium Carbonate content at the expense of cellulose and Si-bearing materials, in the electrode coating (Rissone et al, 1995). The second step, and present one, was to evaluate the effect of the replacement of quartz (100 % SiO_2) with wollastonite (Calcium Silicate, 50% SiO_2-50% CaO) in the E6013 manual electrode coating. The mentioned replacement produced:

- an improvement of the vertical position welding performance together with a slight detrimental effect on the down-hand position, being the typical excellent operational properties of rutile electrodes maintained, on all the types and welding positions;
- a slag basicity increase, evaluated through the Boniszewski Basicity Index (Tuliani, Boniszewski and Eaton,1969);
- a decrease of oxygen and Si all-weld-metal contents;
- no variation in tensile properties, which were inside the expected values for this type of electrodes;
- an important increment of all weld metal toughness;
- a marked decrease of diffusible hydrogen in the deposited metals;
- no modification in the percentages of columnar and refined zones of all-weld metal specimen Charpy-V notch location;
- an augmentation of both acicular ferrite content in the columnar zone and prior austenite grain size, as well as a decrease of the refined fine grain size.

All these facts are shown in a first part of this study (Rissone et al, 1995).

This second part of the present work deals with the arc stability and electrode economical characteristics. The fundamental idea was to study the possibility of improving toughness, as suggested in the first part (Rissone et al, 1995), without spoiling the excellent operational characteristics of rutile electrodes.

From the point of view of arc stability, there are two basic differences between rutile and basic electrodes: the first one have a stable arc independently from the current type and polarity and their metal transfer is quick and in small drops; the others hardly work on DC (-) and on AC welding the arc tends to extinguish during the polarity inversion from negative to positive half-cycle. In addition, the metal transfer is slow and in large drops with an intensive occurrence of short-circuits (Farias, 1993). A previous work on AWS A5.5-81 E7016-C2L/8016-C2 type electrodes, in which the slag basicity was increased with Mg, showed that charge and metal transfers on AC were improved with the increment of the electrode coating Mg content (Farias et al, 1997). As the slag basicity increased with the wollastonite coating rise, due to the replacement of SiO_2 with CaO, it seemed interesting to study how this increase in slag basicity could have affected the stability of the arc and the economical characteristics of the electrodes.

Experimental Procedure

Electrodes

Three experimental AWS E6013 type electrodes, 4-mm diameter, with replacement of quartz with wollastonite, in the electrode coating, were produced. The first one contained 16% quartz and 0% wollastonite; the second one had 8% quartz and 8% wollastonite and the third electrode 0% quartz and 16% wollastonite, being the rest of the constituents the same. Table 1 gives all the coating components of the electrodes. It is important to recall that the idea of replacing quartz with wollastonite, that is to say to replace SiO_2 with CaO, was to increase the basicity of the slag. A reduction of oxygen and an increase of manganese were expected as a consequence. Thus, as seen in Table 1, the amount of metallic manganese (Mn powder) in the coating was reduced as wollastonite was increased, so that the manganese contents of the three weld metals were similar (the balance was made using iron powder) to avoid incorporating another variable. Table 2 presents the chemical composition of the slag produced by these electrodes as well as the Basicity Indexes (BI) calculated according to Boniszewski (Tuliani, Boniszewski and Eaton,1969).

Table 1. Experimental electrodes.

Coating Constituent (%)	Type of electrode		
	6104	6116	6113
Rutile	55.0	55.0	55.0
Quartz	**16.0**	**8.0**	**None**
Calcite	7.0	7.0	7.0
Wollastonite	**none**	**8.0**	**16.0**
Cellulose	6.0	6.0	6.0
Mn powder	9.0	7.5	6.0
Fe powder	7.0	8.5	10.0
Potassium Silicate (ml/kg)	200	200	200

Table 2. Slag composition (AC welding).

Type of constituent	Type of electrode		
	6104	6116	6113
TiO_2	48.9	50.7	52.4
SiO_2	22.3	20.7	17.6
ZrO_2	0.28	0.32	0.29
Al_2O_3	0.35	0.21	0.20
MnO	11.6	9.2	8.0
K_2O	4.3	4.5	4.3
FeO	9.1	7.5	6.1
CaO	3.9	7.7	11.3
BI	0.39	0.44	0.51

BI: Basicity Index (Tuliani, Boniszewski and Eaton,1969).

Weldments

Bead-on-plate weldments in down-hand position were carried out with these electrodes, using ASTM A-36 50x150x6 mm plates on both polarities (DCPE and DCNE) and on AC. Two electromagnetic power sources (DC and AC) and an automatic covered electrode welder simulator (Farias et al, 1997) were used. A computer-aided data acquisition system of programmable frequencies at 12 kHz in each channel (voltage and current), 12 bits, was applied (Farias et al, 1997). Each experiment, conducted according to the welding parameters listed in Table 3, was triplicate. The instantaneous values of arc voltage and current were registered during 6s, totaling 18 s of acquisition for each combination of type of electrode/type of current. A dedicated software was used for treating the instantaneous voltage and current signals acquired (Farias, 1993), aiming at the arc behavior analysis.

Table 3. Welding parameters.

Type of current	I_{rms} (A)	U_{rms} (V)	TS (mm/s)	HI (kJ/mm)
DCEP	188.0	25.0	3.0	1.57
DCEN	185.0	25.0	3.0	1.54
AC	190.0	26.0	3.0	1.65

Irms: mean effective current; Urms: mean effective voltage; TS: welding travel speed; HI: heat input.

Arc Behavior Study

The study of electrodes behavior was based on a methodology that evaluates:

The electrodes economical characteristics, by means of the actual fusion rate (FR = weight of electrode, including coating, burnt out) and the deposition efficiency (DE), and

Arc stability, assessed by considering both the electric charge transfer and metal transfer mechanisms (Farias, 1993; Farias et al, 1997).

All the responses were submitted to a variance analysis (Montgomery, 1984), with a confidence level of 95%, for determination of the significance level (α) of the analyzed effects.

Results and Discussion

Economical Characteristics

The results concerning fusion rate, FR (kg/hA) and deposition efficiency, DE (%), are shown in Table 4. and Figures 1 and 2. As a whole, no prominent detrimental effect on the economical characteristics could be observed in the electrode with 16% wollastonite (6113) when compared to the no-wollastonite-content electrode (6104). Besides, a small amount of porosity in the slag, a little more difficult slag detachment, more spatter and more convexity of the bead surface were the characteristics observed in the highest-wollastonite-content electrode. On the other hand, the intermediate-wollastonite-content electrode (6116) exhibit a bit better fusion rate than the others on DCEP and on DCEN ($\alpha < 1,0$ % on Table 4) (on AC, the variance analysis showed no difference amongst the electrodes, ($\alpha > 1,0$ % on Table 4). Deposition efficiency presented statistically higher values for 6104 only on DCEN ($\alpha < 1,0$ % on Table 4). In all other conditions the variance analysis could not distinguish them (Table 4).

As seen in Table 2, the addition of wollastonite increased the CaO slag content. That means an increase in slag surface tension and slag density. The slag solidification becomes quicker and makes gas evolution more difficult. This effect may cause slag porosity. The bead surface and the slag detachment also may be affected by the increase in the slag surface tension. In spite of these variations in slag properties, there was neither undercut nor porosity in the bead surfaces.

Table 4. Economical characteristics.

Type of Electrode	Type of current					
	DCEP		DCEN		AC	
	FR x 10^{-3}	DE (%)	FR x 10^{-3}	DE (%)	FR x 10^{-3}	DE (%)
6104	12.42	62.0	11.85	66.0	11.53	64.0
6116	13.39	60.0	12.23	64.0	11.38	61.0
6113	12.64	59.0	11.04	62.0	11.29	62.0
α (%)	**0,38**	**16,62**	**0,02**	**0,21**	**24,97**	**13,31**

Fusion rate in kg/hA

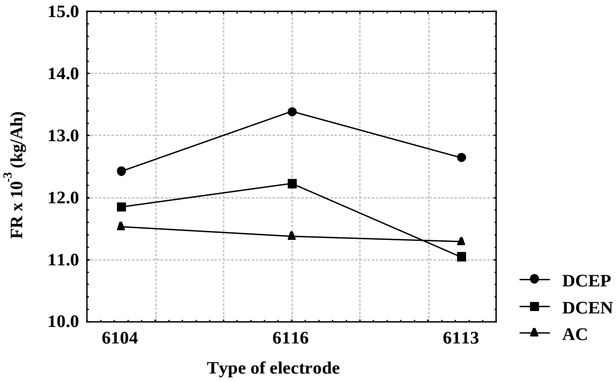

Figure 1. Effect of electrode type on the fusion rate.

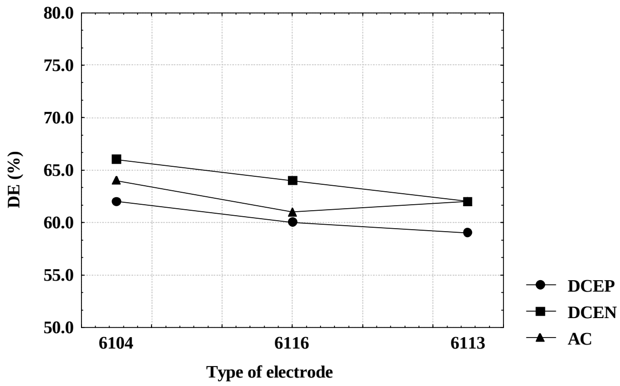

Figure 2. Effect of electrode type on the deposition efficiency.

Arc stability

The study on arc stability was made initially by comparing short-circuit characteristics, that is, its duration and frequency (metal transfer data). It was concluded that actual transfer by short-circuit happens when its duration is longer than 2 ms (Pokhodnya et al, 1991; Scotti et al, 1995). The data treatment software automatically measured a parameter identified by "t_{sc}" (short-circuit time). The software also measured the period between short-circuits and, consequently, the frequency, identified by the parameter "F". The outcome of the software represents the average values of "t_{sc}" and "F" for each experiment.

Table 5 and Figures 3 and 4 show the results of metal transfer characteristics. The figures represent the mean value of each experiment with the same combination (in number of 3). As observed in the table 5 and in the Figure 3, the intermediate-wollastonite-content electrode (6116) tended (very low significance) to present higher short-circuit frequency on DC (this better performance of 6116 electrode was also observed in fusion rate analysis). The behavior on AC, likewise in fusion rate and deposition efficiency, did not show the same.

Table 5. Metal transfer data.

Type of Electrode	Type of current					
	DCEP		DCEN		AC	
	F (Hz)	t_{sc} (ms)	F (Hz)	t_{sc} (ms)	F (Hz)	t_{sc} (ms)
6104	1.28	3.51	1.67	3.39	1.26	3.45
6116	2.50	3.89	3.50	4.00	0.78	3.35
6113	1.33	3.65	0.83	3.61	0.78	3.42
α (%)	**17,86**	**67,89**	**2,68**	**19,33**	**24,54**	**95,95**

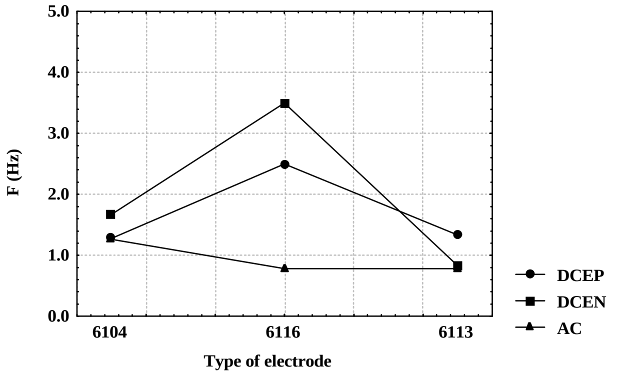

Figure 3. Effect of electrode type on the short-circuit frequency.

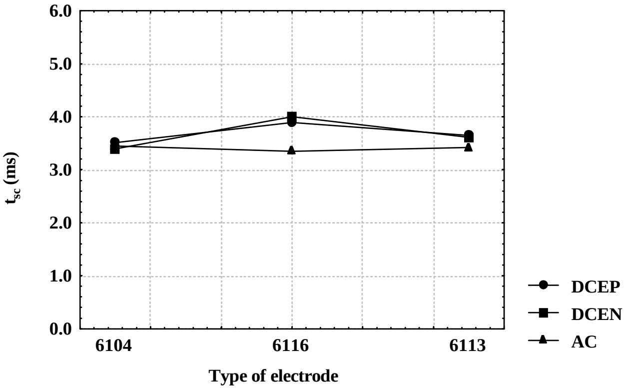

Figure 4. Effect of electrode type on the short-circuit time.

So far, any relationship between "t_{sc}" or "F" and arc stability or operational facility has not been mentioned before in the literature, but longer "t_{sc}" and quicker "F" are characteristics of basic electrodes (Farias, 1993). Thus, in addition to metal transfer, charge transfer characteristic assessment could give another criterion for evaluating the influence of wollastonite. With this purpose, new indexes came up (Farias, 1993).

On DC: FE index represents the electric power spent to restrike the arc after each short-circuit and RE (FE/σ) index, the FE regularity, is calculated by the inverse of relative root-mean-square deviation of the index FE.

On AC: B^+ index represents the mean speed of increase of the electrical conductivity in the inter-electrode space during the positive pre-arc period and RB^+ index, (B^+/σ), indicates the regularity of the electric charge transfer and represents the inverse of relative root-mean-square deviation of the index B^+. On the contrary of the former indexes, B^+ index has been proposed some time ago (Pokhodnya et al, 1980) and its performance verified several times by the authors.

The data treatment software for each experiment calculated all the indexes. Table 6 and Figures 5 and 6 show these indexes on DC considering the electric power spent in all short-circuits (with and without metal transfer). Table 6 and Figures 7 and 8 show the indexes B^+ and RB on AC. The values are the average of the triplication. As Table 6 and Figures 5 and 6 show, there was a small tendency of wollastonite increased electrodes (6116 and 6113) to show better stability on DC (higher FE or RE) nevertheless, these tendency was not statistically significant (α >1,0 %). Otherwise, on AC, whose indexes B^+ and RB are more reliable, they seemed to increase together with the increment of wollastonite.

Table 6. Electric charge transfer data.

Type of	FE ($W^{-1}s^{-1}$)		RE		B^+ ($\Omega^{-1}s^{-1}$)	RB^+
Electrode	DCEP	DCEN	DCEP	DCEN	AC	
6104	1.79	1.92	1.03	0.97	2322	3.45
6116	1.81	2.02	1.09	1.06	2540	3.85
6113	2.30	1.67	1.09	1.08	2945	4.54
α (%)	**5,33**	**34,79**	**81,91**	**66,29**	**0,02**	**0,33**

The extinction of the arc in the short-circuiting (during which the current remains high and, depending on the power source, can even exceed the double of the welding current) takes place in normal welding conditions on DC. This causes temperature to raise to high levels at the tip of the electrode and at the weld pool, thus facilitating the arc restriking process after the drop has been transferred. It was assumed that, in this case, the slag basicity did not affect the arc restriking mechanism because the high short-circuit currents were enough to guarantee the ionization and later restriking. A more careful analysis of Table 6 indicates that the type of electrode influenced neither the facility nor the regularity of charge transfer with DC welding. This was deducted from the analysis of variance, as discussed above.

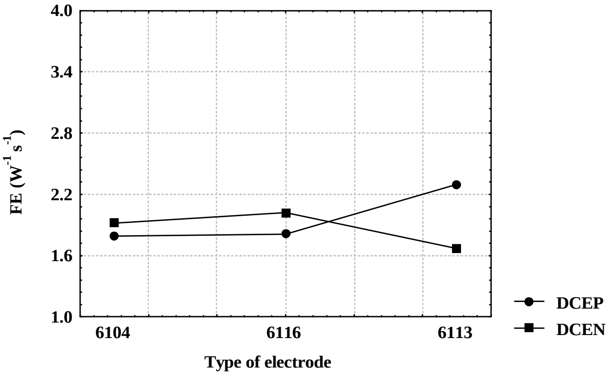

Figure 5. Effect of electrode type on the index FE.

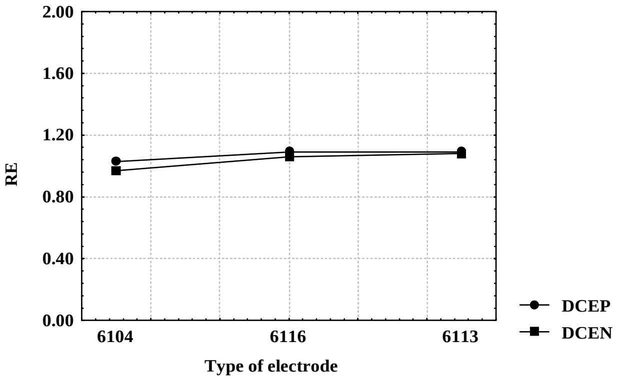

Figure 6. Effect of electrode type on the index RE.

Welding on AC, with a sine wave power source, the current approaches zero at a certain interval during which the arc is maintained by the effect of thermoionic emission. The emission capacity of the electrode, where the cathode will be formed, plays a fundamental role in the restriking of the arc, during the changes of polarity and depends on several factors (Pokhodnya et al, 1991):

1) the temperatures of the electrode, the weld pool and the gas present in the arc column;

2) the composition of the gases present in the arc column;

3) the emission capacities of the electrode and the weld pool;

4) the intensity of the electric field applied to the arc column.

The increase of B^+ and RB^+ indexes (Table 6 and Figures 7 and 8) with the addition of wollastonite may be attributed to the effect of slag basicity. Table 2 and Figure 9 show that the slag basicity increases with the addition of wollastonite on the electrode coating. It is believed that increasing CaO content in slag augments its thermoionic emission capacity. These tendency was also observed in basic electrodes with magnesium powder in the coating. The increasing of coating magnesium content, that means the increasing of slag MgO content, caused a significant increasing in the B^+ and RB^+ indexes (Farias et al, 1997). It's important to emphasize that the higher these indexes the higher the facility of welding on AC.

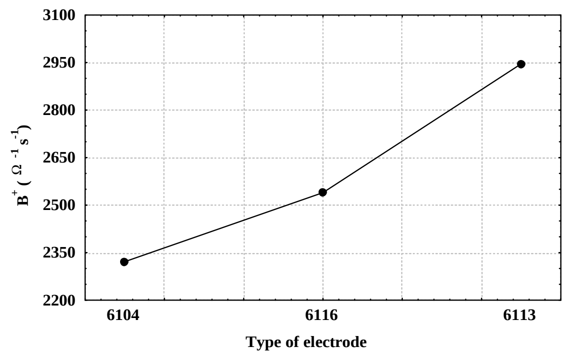

Figure 7. Effect of electrode type on the index B^+.

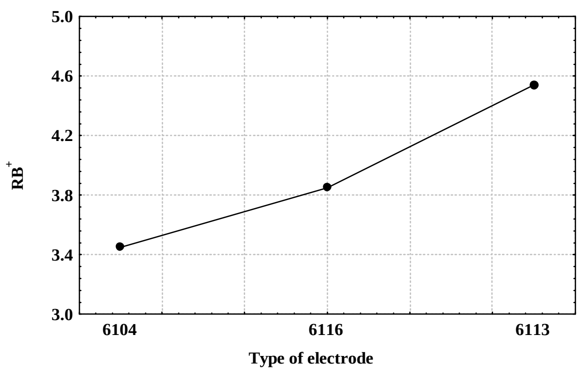

Figure 8. Effect of electrode type on the index RB.

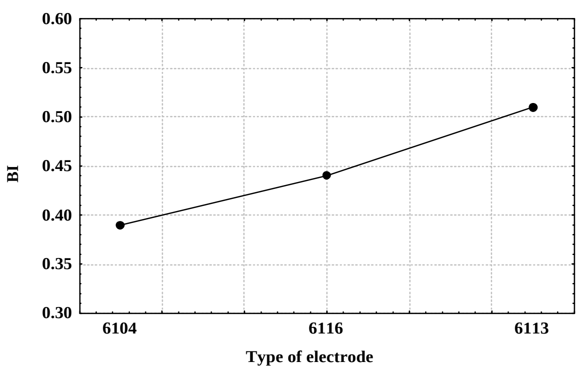

Figure 9. Effect of electrode type on the basicity index.

Conclusion

The replacement of quartz with wollastonite in the coating of an AWS E6013 type electrode did not cause prominent effect on the economical characteristics of the electrodes and did not reduce its arc stability. Actually, there is an improvement of arc stability on AC. The metal transfer mechanism (frequency and duration of short-circuits) was not significantly affected on AC nor on DC. Thus, the excellent operational behavior of rutile electrodes can be maintained by using wollastonite in replacement of quartz.

As the replacement of quartz with wollastonite in the coating increases slag basicity and decreases all weld metal silicon and oxygen contents, it seems possible to increase the weld metal toughness without losing the excellent operational behavior of rutile electrodes.

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