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EXPERIMENTAL ANALYSIS ON THE PERFORMANCE OF SMA WELDING ELECTRODES

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Abstract. *Considered the most traditional and widespread welding process, stick electrodes are differentiated mainly by the chemical composition of their coating, being of cellulosic, rutile, basic, high yield and acid reaction types. In this context, the present study has the main objective of characterizing the performance of different stick electrodes applied in manual welding. To this end, welding tests were performed in the flat and angle joint position, with direct current and alternating current, on SAE 1020 steel plates, being evaluated five electrode specifications: E6010, E6011, E6013, E7018 and E7024. The study is supported by acquisitions of electrical signals from the process, as well as macro-graphic analysis of the weld beads, which enabled the calculation of the dilution of the weld beads. The results showed the static characteristic of the arc and the melting and deposition rate of the electrodes. In addition, the potential of using alternating current with three of the electrodes tested was investigated. These studies showed, in general, the melting and penetration potential of the cellulosic electrodes, the high deposition rate of the basic electrodes, the arc stability of the rutile electrodes, besides showing the high deposition efficiency of the electrodes with addition of iron powder.*

Keywords: *SMAW, MMA, Arc Welding, Fusion Rate, Deposition Rate*

1. INTRODUCTION

The shielded metal arc welding (SMAW) is characterized by its versatility and simplicity of the equipment used. The electrode used in the SMAW process consists of a metal core, which is used as filler metal, and the coating, which refers to the outermost layer of the electrode. Thus, the heat provided by the arc is used to melt the filler metal in the base material, and unlike other welding processes such as GMAW and GTAW, it does not need the provenance of protective gases, since the gases that protect the weld pool during metal transfer are generated with the decomposition of the coating.

Considered of greater relevance to the process, the coating may be made of several types of components, which have mineral or organic origin, but always put together by a binder paste of two distinct types: the sodium silicate-based binder and the potassium silicate-based binder. Often they are mixed in greater or lesser proportion fundamentally defining the classification of the electrodes within the existing standards, because the cores are usually identical. Thus, AWS A5. 1 standardizes the coated electrodes based on the compositions and proportions of the alloy elements present in the coating. They can be of the cellulosic type, which have high penetration and high gas production, supply a large amount of hydrogen to the weld metal and are commonly used in the root pass; the rutile type (with TiO_2 in its composition), general purpose consumables, with medium penetration; The basic type, or low hydrogen, containing better mechanical and metallurgical properties; besides the electrodes considered of high yield, which are basically rutile and basic electrodes with addition of iron powder and have higher deposition rate and greater fluidity of the slag (ESAB, 2005) and also the acid reaction electrodes, consisting mainly of iron oxide, manganese and silicon.

In this sense, the coating acts mainly in the protection of the melt pool, after much of it has become slag, against adversities caused by atmospheric air such as oxidation. Besides protecting the molten metal during solidification, the slag produced also promotes a reduction in the cooling speed of the strand. In addition, the chemical composition of the coating has a fundamental function in the welding process and can contribute to the stability of the electric arc and to promote the improvement of the mechanical and metallurgical properties of the weld by melting in the melt pool near the metal core. Lima II (2006), verified that this is possible mainly due to the alloying elements present in the composition of the coating. In this regard, Kobayashi (1987), has already evaluated the effects of varying the contents in the coating composition, specifically for basic electrodes. The study demonstrated, for example, that for electrodes with increased calcium carbonate there was an increase in specific consumption, a worsening in the surface aspect of the bead, and a decrease in the yield of the electrode. While with the addition of iron powder, there was an increase in consumption and a reduction in yield, without significant changes in the surface appearance of the bead. These papers are just a few examples that denote practical implications of electrode coating composition.

In this context, the selection of electrodes suitable for each specific application is a task that requires a broad view of their characteristics, and in particular the characteristics of the coatings. First it is appropriate to mention that there are three main focuses of attention in electrode selection. One is the degree of penetration that the electrode is capable of producing. The other is the metallurgical quality and the third is productivity and finish. In addition, the results of the electrical effects as a function of the properties of the coatings and where the generated electrical power flows is also a factor that must be analyzed and considered in order to choose the most suitable electrode for a given application. Depending on the type of coating, the power generated may be used more for arc self-management, that is, melting the coating and producing slag, or more for the production of heat to melt the part.

For this reason, one of the main objectives of this work is to also survey the relationships of voltage with current, verifying the resulting power and associating it with the final characteristics of the welds. This also involves welding with alternating current, commonly used in more rudimentary equipment, being a viable alternative to test the stability of the electrodes, because it is a situation that highlights the characteristics of the coatings. The importance of this understanding about the electrical factors of the process can justify some operational aspects such as momentary extinctions of the arc in alternating current, for example. This effect is relevant, especially in metal transfer, when the electrode periodically reaches the melt pool. When the contact between the melt pool and the electrode is broken, there is a tendency to be explosive, vaporizing part of the material and generating spatter, besides the change in the average current and the melting capacity of the base material. Thus, AC arcs tend to extinguish during the passage through the zero point (0 A), resulting in arc instability and spatter generation during re-ignition.

To understand the complex of factors that lead the electrodes to have their properties, here are presented some experiments and a brief discussion about the effects of different specifications of coated electrodes, considered in this study as the main ones used industrially. The study has as technological basis the verification of the static characteristic of the arc with the different types of electrodes (cellulosic, rutile and basic), measurement of the dilution and geometric characteristics of the weld seams by means of macrographic analysis, besides measuring and evaluating the melting and deposition rates of the electrodes. The potentiality of using the electrodes with alternating current (AC) was also briefly evaluated by measuring the electrical signals of current and voltage, in order to compare the stability of the application of AC with the use of different types of electrodes.

2. Methodology

Investigations were carried out on the static characteristic of the arc and on the melting and deposition rates of the electrodes. For this purpose, manual welding of the bead-on-plate deposit type was performed with an IMC Inversal 300 welding power source, in the flat position (1G) with direct current in positive polarity (CC+) in the range between 60 and 160 A. The electrical data from the welding process was obtained with a portable welding electrical signal acquisition system (IMC - SAP v.4) with a sampling rate of 5 kHz. These tests were performed on SAE 1020 steel plates with 9.6 mm thickness as base material. The electrodes submitted for testing to obtain the data were the electrodes, specified by AWS A5.1, E6010 and E6011 (cellulosic), E6013 and E7024 (rutile), the latter with 50% iron powder added to the coating mixture, and electrode E7018 (basic), with iron powder added in the range of 25 to 40%. All electrodes had a core diameter of 3.25 mm. In this step, measurements were taken of the mass of the specimen and electrode before and after welding, as well as the initial and final length of the electrode core, and the arc time. In calculating the melting rate (*Tf*), Eq. (1) was used, where *Mf* refers to the mass of electrode core metal melted by arc time *t*. The calculation of the deposition rate (*Td*) in the base material given in Eq. (2), where *Md* represents the mass of metal deposited by the arc time, and through the ratio between *Tf* and *Td*, the deposition efficiency (*Ef*) was calculated, as shown in Eq. (3).

$$Tf = \frac{Mf}{t} \quad [kg/h] \qquad (1)$$

$$Td = \frac{Md}{t} \quad [kg/h] \qquad (2)$$

$$Ef = \frac{Td}{Tf} \times 100 \ [\%] \qquad (3)$$

After the initial tests to verify the melting and deposition rate, the joint welding was performed on fillet type T-joints (2F position) on SAE 1020 steel with 9.5 mm thickness, in order to verify the penetration profile and the dilution of each electrode with the base material. The welding current employed in these tests was 120 A for all electrodes, besides two additional tests with 140 A, specifically for electrodes E6013 and E7018. These specimens were then submitted to metallographic preparation, cut in cross-section, ground with 80 to 600 grit sandpaper, polished with alumina suspension with an average particle size of 1µm, and chemically attacked with the reagent Nital 2%. After the chemical attack, it was possible to analyze the macrographs of angle joints to evaluate the added area and penetrated area of the welds performed, these areas are shown respectively as A and B in Fig.1. ImageJ image analysis software was used, to perform the measurements that enabled the calculation of the dilution (ʒ), using Eq. (4).

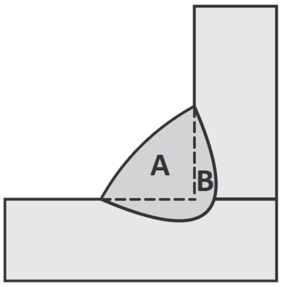

Figure 1. Geometric representation of the added area (A) and penetrated area (B) of a weld bead.

$$\delta = \frac{B}{A+B} \times 100 \quad (4)$$

To verify the welding stability with the different electrode specifications, in the last step of the study the potential of using the electrodes in alternating current was verified, by evaluating the electrical signals obtained from the procedure. The welding of bead-on-plate deposits was performed manually in the flat position (1G) on 9.5 mm thick SAE 1020 carbon steel plates. An electromagnetic welding source TIGPOP 200, which allows the use of alternating current, was used in this test, along with electrodes E6010 (cellulosic), E6013 (rutile) and E7018 (basic).

3. Results and discussion

3.1 Effects on Voltage, Current, Power and Geometry Relationship

The acquired information regarding the static characteristics of the arc was plotted in a graph, presented in Fig. 2. It can be clearly seen that electrode E6010 presents the highest voltage among all the electrodes, consequently the highest power (approximately 3100W), while electrode E6011 with the same type of coating except for the agglomerate that is potassium silicate, presents a voltage similar to that of electrode E7018. The explanation for the high voltage of E6010 finds easy resonance in literature such as Wainer, Brandi and Mello (1992) with the explanation that the cellulose in the arc region produces a large amount of hydrogen (in addition to CO2 and CO), forming a plasma jet of high power. The penetration of E6010 is effective with a penetrated area of 22 mm^2, an added area of 17 mm^2, resulting in a dilution of approximately 56%, as can be seen in Fig. 3.

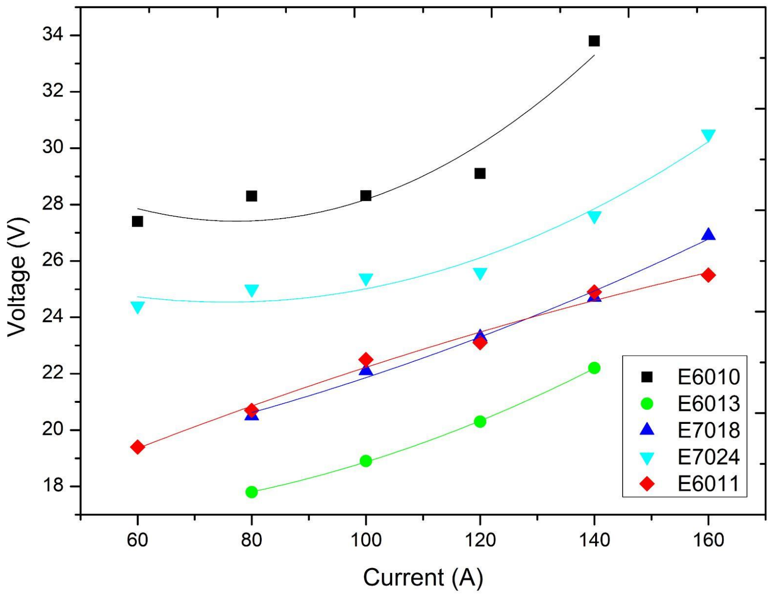

Figure 2. Static characteristic of the arc in SMA welding.

Also evident is the behavior of electrodes E6011 and E7018, which showed similar behavior with respect to the voltage signal for the same welding current, being the power of 2600W and 2700W respectively. The conjecture that can be made is that the voltage of the latter electrode is relatively high for two factors. One is that its coating, being relatively thick (external measurement of 5.6 mm versus 4.5 mm for E6011), causes the arc to be necessarily larger than in the case of cellulosic. The other factor is the larger amount of slag produced that requires much more power than is needed to ionize gases. Therefore, greater power is one of the justifications for obtaining greater penetration, as long as there is not too much slag. Thus, from a thick coated electrode, and even worse, when it contains iron powder, high penetration is not expected. The E6011 electrode, resulted in 12 mm^2 of penetrated area and 20 mm^2 of added area, with the equivalent of 38% dilution while E7018 resulted in 4.6 mm^2 of penetrated area, 29 mm^2 of added area and 13% dilution. The strand manufactured with this electrode, also showed subtle lack of root penetration, as can be seen in Fig. 3. In addition, the E7018 electrode presents an operability only slightly inferior to the E6013. This good workability is due to the presence of iron powder in the coating. The electrical power was approximately 2700 W, about 10% higher than for E6013.

The rutile electrode E6013, whose agglomerate is potassium silicate, is the one that requires the lowest voltage of all the electrodes, and therefore the resulting welding power shown in Fig. 2 was only 2500 W. It is not so much lower than electrode E6011, but because of the greater amount of slag formed, penetration is low. Under these conditions the weld is failing due to incomplete fusion in the root, with occasional voids such as the one shown in Fig. 3. The penetrated area was only approximately 4.7 mm^2 and the added area was approximately 19 mm^2, resulting in a dilution of approximately 20%. The low arc voltage formed by this electrode is due to its character of easy ionization due to the potassium, resulting from the decomposition of potassium silicate, and due to the elements resulting from the rutile (TiO2). Because of these characteristics, it is a preferred electrode for less skilled welders and for jobs without many technological requirements.

Regarding the electrode E7024, which presented a relatively high voltage in compared to other rutile electrodes, the higher power is due to the high amount of coating mass present in this electrode, with 50% iron powder added, with this higher energy is required to melt this coating. The result of the E7024 electrode, presented in Fig. 3, was 2.2 mm^2 of penetrated area, while the added area reached 24 mm^2, with dilution equivalent to 8.4%, however, it indicated incomplete penetration for the conditions tested.

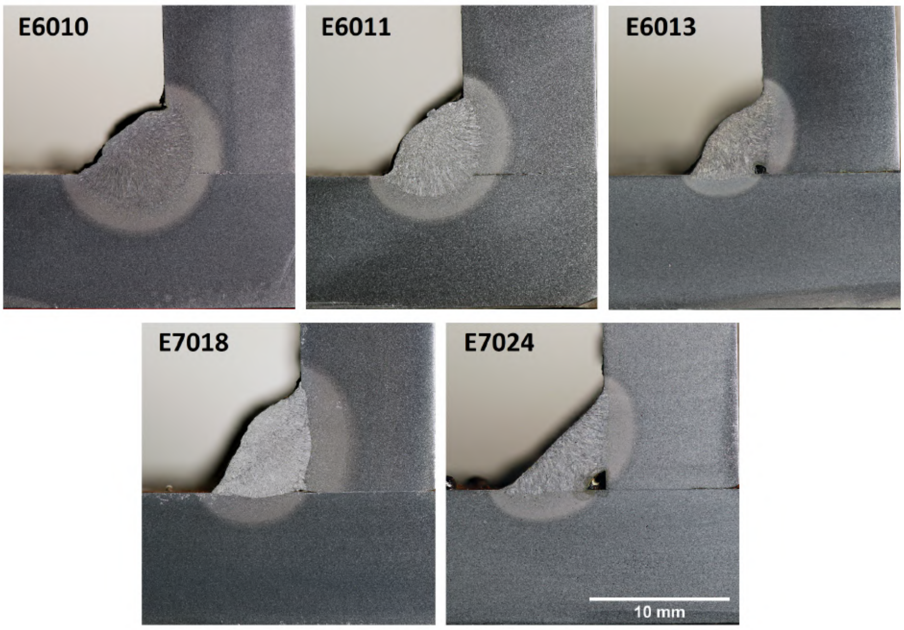

Figure 3. Macrographs of the welds with 120 A.

Comparatively, the results of the electrodes that presented incomplete penetration match the widespread descriptions, being referred to as lower penetration electrodes, and therefore can be used for welding thin plates, coatings or filling bevels (ESAB, 2005). This was proven, in the present study, by considering increasing the welding current level to 140 A for the electrodes that presented incomplete root penetration defects, in order to mitigate the occurrence of this defect. Thus, it was possible to prove the real performance of E6013 and E7018 electrodes in joining welding. With this current level, both electrodes maintained practically the same area of added material (18 mm^2 for E6013 and 29 mm^2 for E7018), and only the penetrated area increased to 6.9 mm^2 and 7 mm^2 for E6013 and E7018 respectively. However, despite the application of a higher current, the weld bead from E6013 still showed incomplete root penetration, but at a much lower level compared to the test with 120A. As expected, the increase in the electrical current is a significant factor in mitigating defects such as the one presented. On the other hand, although the penetration value of the E7018 electrode was relatively low, complete root penetration was achieved. The macrographs obtained from these experiments can be seen in Fig. 4.

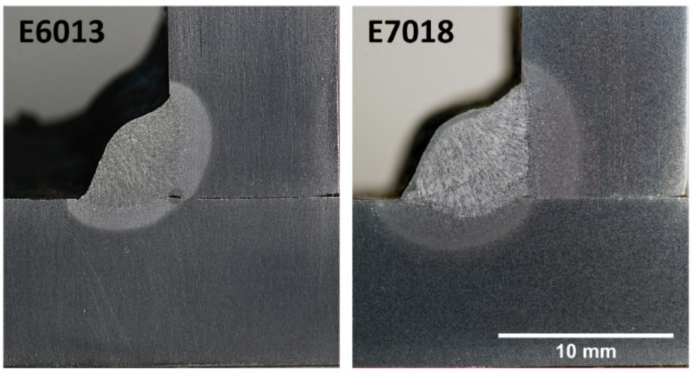

Figure 4. Macrographs of the welds with 140 A.

3.2 Electrode Fusion and Deposition Rate

Regarding the results of the tests to verify the melting rate of the different electrodes, all calculated values were plotted in a graph, illustrated in Fig. 5. The electrodes that presented the highest melting rate, in this study, were the cellulosic electrodes, E6010 and E6011, a fact that is supported due to the high power generated for this electrode specification, which matches some commercial descriptions of these electrodes, which indicate them as deep penetration electrodes (ESAB, 2005). This phenomenon can also be explained by the fact that these electrodes have a smaller coating mass compared to the others, and the coating diameter is smaller. The energy generated by the arc is concentrated mainly in the fusion of the electrode core and the base material, resulting in deeper penetration and less addition of alloying elements. The electrodes E6013 and E7018 presented intermediate results regarding the melting rate when compared to the other electrodes evaluated. This fact is consistent with the slightly lower power of these electrodes. The E7024 electrode showed the lowest melting rate compared to the other electrodes tested, below 1kg/h for the maximum current evaluated (140A), despite the high power generated in this electrode. This effect occurred because much of the energy generated by the arc is used to melt the high mass of coating contained in this electrode (larger total diameter), whose composition contains 50% iron powder.

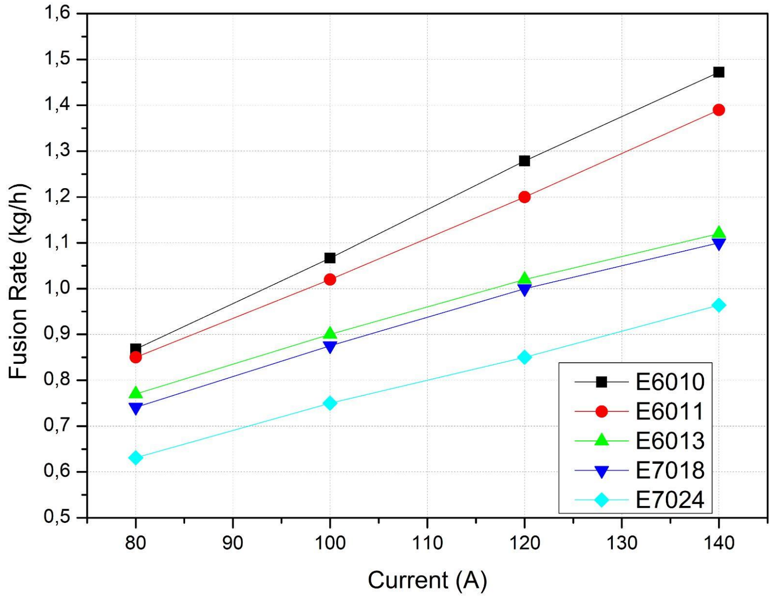

Figure 5. Melting rate for the different 3.25 mm electrode specifications.

Regarding the tests performed to verify the deposition rate, which were also plotted in a graph, shown in Fig. 6, the electrodes presented the exact opposite behavior. From this finding, the results suggest that one does not necessarily obtain a higher deposition rate when the fusion rate is also high. That is, in this case, the cellulosic electrodes that presented high power arcs, considering the static characteristic of the arcs presented in Fig. 2, also presented high mass loss due to excessive spatter generation. This reason may be an indication of the cellulosic electrodes presenting low deposition rate, while the others (E6013, E7018 and E7024), presented high deposition rates. The latter, being rutile and basic, are indicated for welding thin plates or for applications that require higher deposition rates and lower penetration, such as repair operations or filling beveled joints. This is especially true of the E7018 and E7024 electrodes, which can be justified by the addition of iron powder to the coating. The iron powder melts near the weld pool and this material adds to the mass of the weld bead, thus generating an excess deposition compared to the electrode core metal alone. Moreover, the presence of other elements in the composition of these electrodes, such as iron powder or titanium dioxide (TiO_2), in the case of rutile electrodes, can corroborate to this greater deposition, considering that these elements contribute to the stability of the arc, consequently generating less aggressive arcs and less penetration.

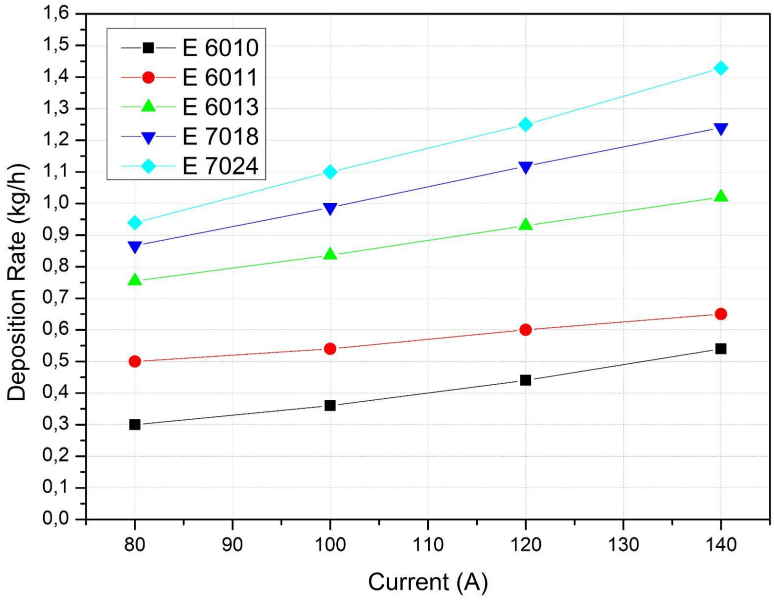

Figure 6. Deposition rate for the different 3.25 mm electrode specifications.

From the results obtained regarding the fusion rate and deposition rate, the deposition efficiency was measured for each type of electrode, indicated in Fig. 7. The deposition efficiency represents the ratio between the deposition rate by the fusion rate, so that it correlates the amount of material mass that effectively generated the weld bead with the mass consumption of the electrode by the welding process. With the data obtained, the deposition efficiency percentages of the electrodes used were plotted in a column chart.

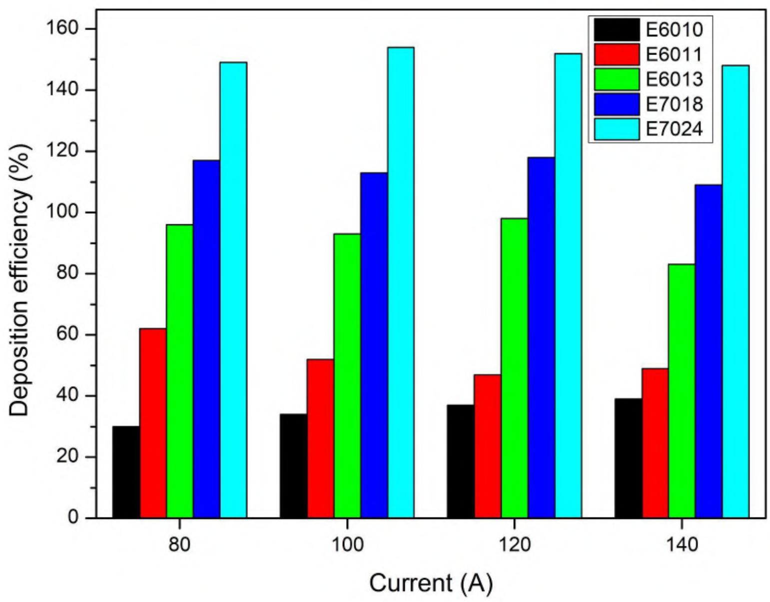

Figure 7. Deposition efficiency for the different 3.25 mm electrode specifications.

It is possible to see that the cellulosic electrodes were the ones that presented the lowest percentages of efficiency, being the least efficient electrode E6010, with less than 40% in all current steps, followed by E6011, which presented a slightly higher efficiency, however, below 60%. The other electrodes showed higher efficiency results compared to the previous ones, with E6013 obtaining a range of 90 to 100% deposition efficiency, and interestingly, electrodes E7018 and E7024 obtained efficiency above 100%, around 120% and 152% respectively. This result is controversial for a process that part of the materials and elements that constitute the electrodes are converted into gases, fumes, slag and other impurities felt. This is only possible due to the composition of the coating, which presents a high percentage of iron powder in its composition, as mentioned above in this article. In addition, because they are indicated for high material deposition procedures, the total diameter of these electrodes (core and coating) is relatively larger compared to the other electrodes used. Thus, considering that all the measurements were made only with the core of the electrodes, the metal present in the coating (mainly iron powder), was melted together with the fusion puddle, making the efficiency higher than 100%. In this context, it is evident that the cellulosic electrodes (E6010 and E6011) are electrodes designed to melt the part, not having any chamfer filling attributes. In contrast, electrodes E7018 (basic) and E7024 (high iron powder - about 50%) are high deposition rate electrodes.

3.3 Electrodes Performance in AC Welding

Considering that the electrode specifications indicate the best conditions of use with direct current (DC) or alternating current (AC), experiments were performed in order to obtain data regarding the process operationality and understand some practical reasons why some coated electrodes are not suitable for welding with AC. In addition, the use of AC in SMAW can be a way to verify the stability of the electrodes, as it exposes different characteristics depending on the coating.

Almost never evidenced by the manufacturers, it was verified, through analysis of the electrical signals of current and voltage of the process a blunt characteristic that occurred significantly and distinctly in each electrode specification. Due to the high sampling rate of the measuring equipment, an arc extinction was observed, i.e., a momentary extinguishing of the arc (0 A) for the three electrode specifications (cellulosic, basic, and rutile) using alternating current. However, electrodes E6013 (rutile) and E7018 (basic), which are indeed suitable to be used DC and AC, were found to have an average arc extinguishing time equivalent to 3 ms, as indicated by the current and voltage oscillograms in Figs. 8 and 9. On the other hand, the E6010 electrode, specified for DC welding only, resulted in an average arc extinction time of 9 ms, as can be seen in Fig. 10. This can be explained by the composition of the binder of E6010, which is composed of sodium silicate, i.e., an element of higher ionization potential compared to potassium. Thus, the higher the ionization potential, the more difficult it will be to reopen the arc, because it will also require more energy to reopen it after extinction. This is proven by the voltage peaks that are generated after switching to positive polarity, which are higher for the cellulosic electrode. Although the periods evidenced in the oscillograms were small, this behavior was repeated in the total acquisition time obtained. In the present study, this result was attributed to the reason why this electrode is not indicated for welding with alternating current.

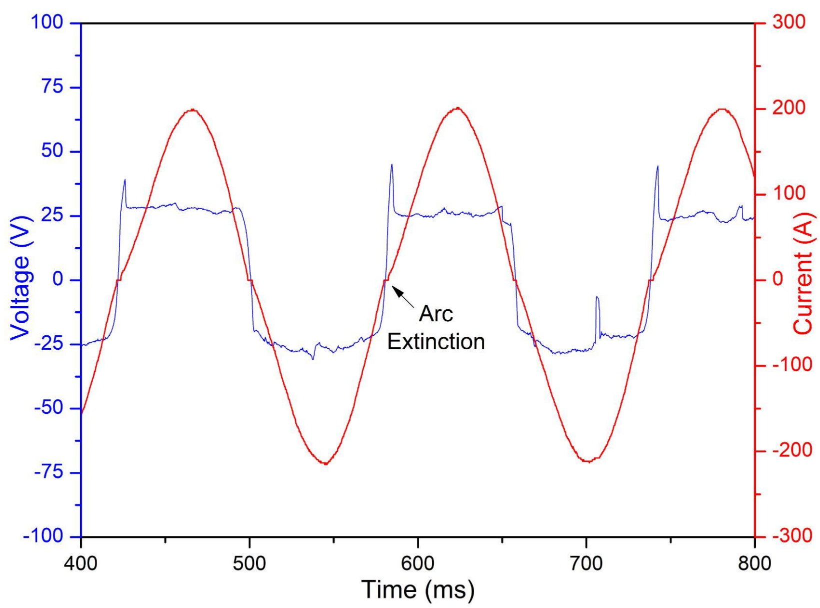

Figure 8. Voltage and current signals obtained in AC welding with E6013.

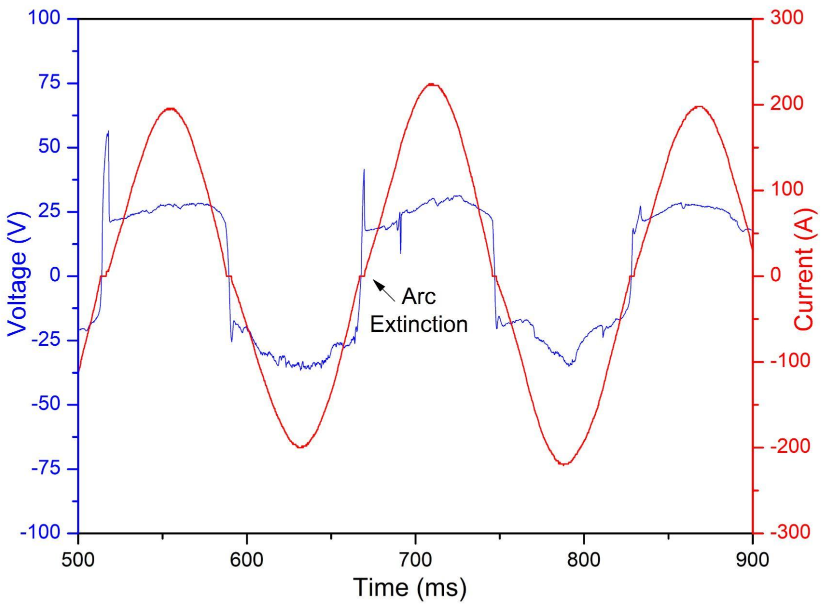

Figure 9. Voltage and current signals obtained in AC welding with E7018.

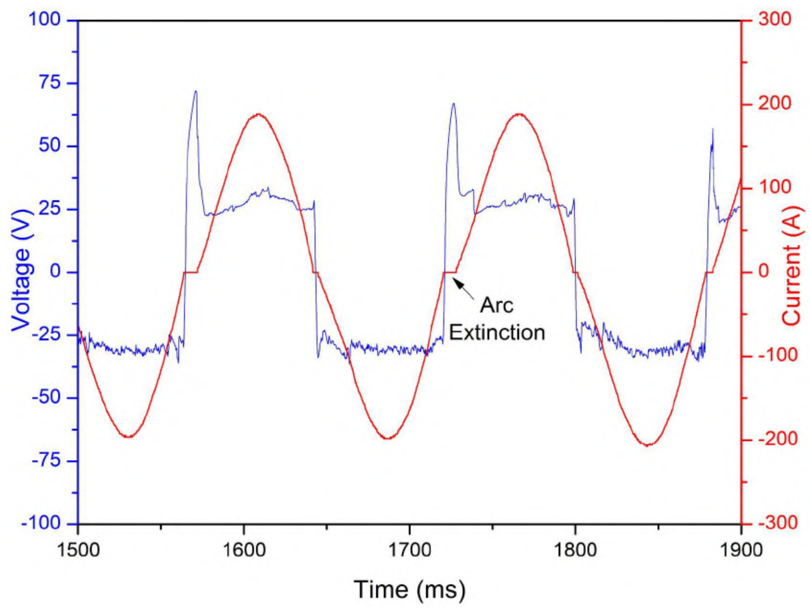

Figure 10. Voltage and current signals obtained in AC welding with E6010.

4. Conclusion

In this study it was possible to show the performance of the main electrodes used industrially, especially in relation to penetration and deposition levels. Therefore, something that becomes evident is the importance of the proper application of the electrode in specific situations, because they presented relatively different results for the same welding current, especially in the arc power and consequently presenting totally different results of penetration and dilution. In addition, many experienced welders/operators use the ease of execution of the process, as well as a good surface aspect of the bead, to evaluate the quality of the weld. However, the results obtained in this study suggest that this is not necessarily a requirement of good welds, and the E6013 electrode was the one that presented a relatively better operability, according to information collected from the operator. However, disregarding the base material used, this electrode showed incomplete root penetration. On the other hand, the E6010 electrode, whose operation is more aggressive and usually with high spatter rate, showed complete and deep penetration. Furthermore, it was possible to prove, by means of appropriate methodology and measuring equipment, some effects of alternating current on the main types of coatings.

5. References

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