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A novel approach for microbial corrosion assessment

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***Abstract*—Materials corrosion in presence of bacteria (Microbiologically Influenced Corrosion, MIC) is an important issue for components deployed in industrial applications and marine environments, where unexpected and fast degradation is often observed. For these reasons, finding new testing methodologies to assess the behavior of different materials in these conditions is a topic of clear interest. This paper describes a new approach based on the use of microbial fuel cells, which are exploited to have known and controlled conditions during the test. The sample is immersed in an environment where the presence and activity of electroactive bacteria are easily monitored measuring the currents flowing between the electrodes of the cell. Then, after connecting the sample of the material under study, reactions occurring on its surface can be monitored and its corrosion resistance can be assessed. This novel methodology is simple, easy to deploy and can be proposed to assess microbial corrosion resistance of metals and alloys, monitoring at the same time the biofilm grown on the metals surface.**

***Index Terms*—Microbiologically Influenced Corrosion; Microbial Fuel Cell; Electrochemical Impedance Spectroscopy; Corrosion; Materials Characterization**

I. Introduction

MICROBIAL corrosion, also known as Microbiologically Influenced Corrosion (MIC), is a corrosion phenomenon often encountered in industrial plants, pipelines or subsea structures [1]. It basically involves the presence of three elements: metal, electrolytic solution and micro-organisms. Bacteria can initiate, facilitate or accelerate corrosion reactions on metal surface, leading to degradation of the component put in service in that particular environment [2]. Because of the importance of this corrosion phenomenon, both in terms of number of cases and of possible economic losses, many are the attempts to find specific methodologies to study it.

Methodologies commonly employed to study MIC can be divided into two major groups: field tests and laboratory tests. In the former case, the material is tested directly in the environment where it is used; this provides the advantage of having results directly applicable to the system under study, but, on the other hand, leads to long experiments and to great difficulties in discriminating the effects of individual parameters during the test [3] [4].

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Laboratory tests are usually based on electrochemical measurements, such as metal open circuit potential monitoring, Electrochemical Impedance Spectroscopy (EIS), polarization resistance and Electrochemical Noise Analysis (ENA) [5]. Main limitations of these approaches are connected to the difficulty in carrying out accelerated tests avoiding any alteration of the microbial activity in order to not get to misleading conclusions [6].

In addition, another issue in MIC testing is the choice of using a single bacterial strain or an inoculum containing a wide variety of bacteria. In the former case, studies on the effect of specific types of bacteria on metal corrosion can be performed, but generally it is difficult to derive information about the overall behavior of the material. Actually in a real environment a great variety of bacteria is present and this modifies their activities and their role in the corrosion processes. Collaborative behaviors between different bacteria strains can occur inside the biofilm, leading to harsher conditions for the material under investigation [6].

A unique solution to arrange a fast and reliable methodology specifically suited for MIC, is still missing in scientific literature. An interesting solution proposed by Little [7] is the Dual Cell Technique: two samples of the same material are immersed inside two identical electrochemical cells separated by a membrane and then connected to a zero resistance ammeter. Bacteria are added into one of the two cells and the galvanic current between the two specimens is monitored in order to study MIC susceptibility of the material versus the sterile conditions. This solution has the advantage of having the possibility of using real inoculum, however, despite it is a theoretically elegant experiment, this technique has been rarely used, perhaps because of the difficulty in the realization of the test.

Another interesting solution, which allows one to use real inoculum, is to use Microbial Fuel Cells (MFC), innovative tools able to convert organic matter into energy thanks to the activity of bacteria [8] [9]. Actually, mechanisms involved in the electron transfer to and from the electrode, which are at the base of the operation of a MFC, are the same responsible for corrosion processes [10]. An approach similar to that of the Dual Cell technique proposed by Little, is therefore the dual chamber MFC. In this case bacteria are added to both chambers of the fuel cell, one in aerobic conditions and one in anaerobic conditions. A current arises, due to the different biofilm present on the metal surfaces, and mechanisms of microbial corrosion can be studied both in aerobic and anaerobic conditions. In the proposed system, a further simplification

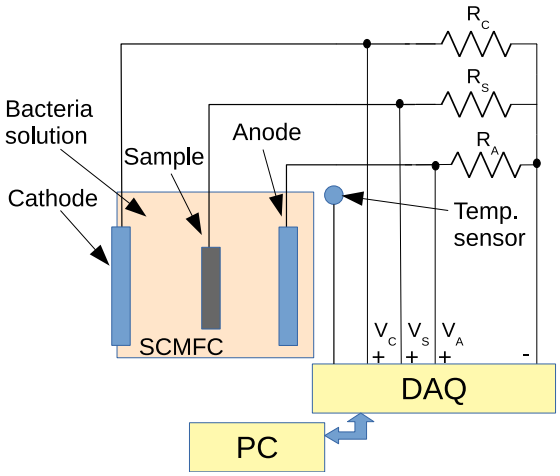

Fig. 1. Block diagram of the measuring system: the SCMFC with the carbon cloth anode, the air-breathing cathode and the sample as the third electrode; the three resistors, the LM35 temperature sensor and the Digital Acquisition board (DAQ) connected to a PC.

has been made, as it involves a Single Chamber Microbial Fuel Cell (SCMFC). In this case, described in the following sections, aerobic reactions take place on an air-breathing cathode [11] and the sample is immersed in the electrolytic solution in anaerobic conditions. As soon as bacteria colonize the metal surface, it is possible to measure a current flowing between the sample and the aerobic cathode, highlighting the growth of the biofilm on the sample and the reactions catalysed by bacteria.

II. Measuring system

In order to perform the microbial corrosion test, a sample of the metal under study is immersed inside a solution containing bacteria and connected to the anode of a Single Chamber Microbial Fuel Cell (SCMFC) [14]. The current that flows in the cell is measured as a function of the immersion time in order to collect information on the bacteria induced metal degradation and on the microorganisms activity.

The proposed solution is based on the monitoring of the current originating from the sample which allows monitoring the formation of the biofilm onto the metal surface. Such a biofilm can change the electrochemical conditions and thus influences the corrosion process. As a matter of fact, the anodic current measured in the SCMFC can be correlated to two phenomena whose effects are superimposed: the oxidation of the metal and the bacteria metabolism which oxidate bioavailable organics. In both cases, electrons are transferred to the air-breathing cathode, where oxygen is the ultimate electrons acceptor after several redox reactions of electrochemical, biotic and abiotic character. Eventually, measuring the cathode current allows assessing the bacteria activity, ensuring therefore that the corrosion test is carried out in conditions favorable for biofilm growth.

A. Measuring system block diagram

The block diagram of the measuring system specifically designed to monitor the corrosion evolution in the presence of electroactive bacteria is shown in Fig. 1. The measuring system is composed of:

- A Single Chamber Microbial Fuel Cell (SCMFC). The fuel cell can be arranged to have any dimension even though small devices are probably a simple and cheap solution able to provide all the details required to monitor the corrosion processes. SCMFC is basically a two electrodes cell, filled with an electrolytic solution containing the bacteria inoculum. One of the electrodes acts as air-breathing cathode, using oxygen as terminal electron acceptor; the other electrode, which acts as the anode, is completely submerged in the electrolytic solution and not exposed to the air, so that anaerobic reactions occur on its surface [15,16]. This way the two electrodes tend to assume different electrochemical potentials with an open circuit voltage difference usually of the order of $400\ \mathrm{mV}$. In an SCMFC cell, bio-induced current/voltage signals depend on the interaction of bacteria growing on the electrodes and, within certain ranges, anodophilic bacteria produce current/voltage signals proportional to the oxidation of bioavailable organics. Consequently, the presence of biodegradable organics in the solution leads to current/voltage generation and therefore the cell is able to produce an electric current circulating between anode and cathode [17,18]. Corrosion phenomena are related to the bacteria activity, which is related to the current flowing from anode to cathode, so, since during microbial corrosion studies the power production is not one of the purposes, the cell can be set to operate maximizing the current even though at the expense of the output power. Eventually, a third electrode made by the metal (sample) whose microbial corrosion behavior has to be assessed, is placed in the operating SCMFC, in a condition that assure the presence of bacteria activity.
- A set of resistors (R_S, R_C and R_A) which are employed as shunts to monitor the current evolution. Even though this is not the only possibility as other approaches based for example on zero-gauss current sensors could be used, this setup is extremely cheap and can be used to arrange a simple measuring system. To perform the corrosion test, resistance values are set to maximize the cell current, so as to have a high bacteria activity; the minimum resistance values is limited only by the measuring system sensitivity.
- An analog to digital acquisition board (ADC) which is used to measure the voltage drops on the shunts and therefore to monitor the current evolution. Several solutions can be used for this block such as digital acquisition boards or microcontroller based boards. The former are more suitable and flexible to design the system, the latter are extremely cheap using solutions as an example based on Arduino boards [19]. These solutions would also decrease the overall cost of the entire measuring system, avoiding the use of a dedicated PC. In addition to the current measurements, also the temperature has to be monitored as this is a critical parameter in microbial corrosion tests since the bacteria activity is strongly

inhibited when temperature decreases.
- A PC which is either used to manage the system, in the case the ADC block requires it, or only to store the measured data.

In the proposed measuring system, the current flowing from the sample I_S, the current flowing to the cathode I_C, and the current flowing from the anode I_A can be obtained as:

$$I_S = \frac{V_S}{R_S} \tag{1}$$

$$I_C = \frac{V_C}{R_C} \tag{2}$$

$$I_A = \frac{V_A}{R_A} \tag{3}$$

where V_S, V_C, and V_A are the voltage drops on R_S and R_C, and R_A, respectively.

The circuit enables a simple check of the system operation since the currents have to obey the Kirchhoff's current law:

$$I_A + I_C + I_S = 0 \tag{4}$$

Any deviation of the current sum from zero has obviously to be considered either due to the measuring uncertainties or to a system malfunctioning.

The voltage drop between anode and cathode, which is the operating point of the SCMFC, is simply:

$$\Delta V_{AC} = I_A \cdot R_A - I_C \cdot R_C \tag{5}$$

This voltage can be controlled by suitably choosing the value of the resistors so that any SCMFC load condition can be easily implemented.

B. Experimental setup

In this study the experimental measuring setup was realized by using a Single Chamber Microbial Fuel Cell (SCMFC) of the type shown in Fig. 2. This SCMFC is a Pyrex® bottle of 0.125 L volume. Anode and cathode are carbon clothes with a living biofilm on their surfaces [12] [13]. The fuel cell operates thanks to the voltage drop between the two electrodes due to the different environmental conditions. The anode is immersed in the electrolytic solution and it is colonized by anaerobic bacteria, as the solution lacks oxygen; on the other side, aerobic bacteria are present on the air-breathing cathode which is exposed to the external environment [14]. The anode inside the solution is square shaped and has surface of about $25\ \mathrm{cm}^2$; the cathode has a circular shape, with a surface of about $5\ \mathrm{cm}^2$.

Using the same material for anode and cathode ensures that no current flows through the cell in the absence of bacteria, since in this condition anode an cathode would have the same potential.

Mild steel (Q-panel standard test substrate, purchased by Q-lab) and stainless steel samples (AISI304 by Goodfellow) were used to assess the feasibility of the proposed measuring system to study the microbial corrosion behavior of different metals. The metal samples were mounted in a polymeric resin in order to have an electrode exposed area of 10 mm $\times$ 10 mm; the samples were then polished on abrasive paper till 2000 grid, rinsed in deionized water and dried.

Fig. 2. Picture of the Single Chamber Microbial Fuel Cell: a Pyrex®bottle of 0.125 L volume equipped with the air-breathing cathode on the opening on the left side, the anode connected through the small opening on the right side and the big opening on the top for positioning the sample electrode.

The microbial corrosion tests were performed in the SCMFC cell filled with an electrolytic solution containing the bacteria inoculum; the inoculum was sludge collected from an anossic tank of a wastewater plant, in order to guarantee a wide variety of bacteria and perform tests in a real condition. The anaerobic conditions inside the solution guarantee a quick electroactivity in the cell. Sodium acetate was used as the carbon source for the bacteria inside the fuel cell. Tests performed by immersing the specimen employed in the test in a solution containing sodium acetate without inoculum highlighted the absence of corrosion, at least for the time intervals of this study.

The acetate was added to the solution when the current flowing between anode and cathode dropped to about 15% of the initial value. After each acetate addition, its concentration reached about $3\ \mathrm{g/L}$, a value which allows having stable conditions for more than 6 days. All tests were carried out in a thermostatic chamber at a temperature of $30 \pm 3\ ^\circ\mathrm{C}$. The DAQ system was realized by using a National Instrument USB6216 DAQ board. This board contains a 16 bit ADC, is equipped with 16 single-ended input channels and is capable of working with an input range of ± 0.2 V. Some preliminary tests [20] carried out by using $R_C = R_A = R_S = 100\ \Omega$ revealed that the expected currents are of the order of 0.6 mA.

Fig. 3 shows the current evolution during a test performed on a mild steel sample. As it is possible to observe, the current (I_S) starts flowing from the sample to the cathode since the beginning of the measurement, with a simultaneous reduction of the current flowing from the carbon cloth anode (I_A). An I_S sharp increase is measured immediately after test beginning, as bacteria started immediately colonizing

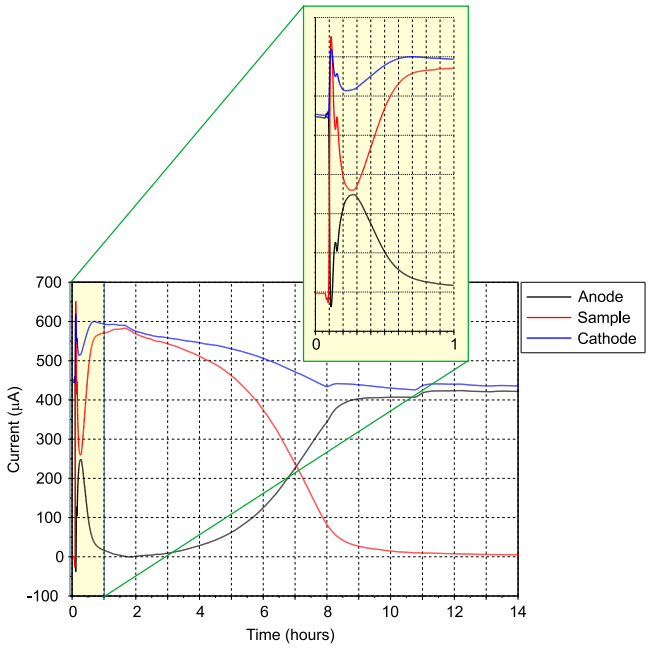

Fig. 3. Current evolution in the microbial fuel cell during a test performed on a mild steel sample for 14 hours. I_A, I_C and I_S trends as a function of time are shown. The microbial corrosion attack starts immediately after the exposure of the sample to the electrolyte, as confirmed by the immediate increase of all current values (as can be observed in the expanded plot).

the mild steel surface. The sample becomes the electrode preferentially providing electrons to the cathode, due to the superimposition of two phenomena: sodium acetate oxidation (related to bacteria metabolism) and metal oxidation. The I_S value is due to these two contributions, which cannot be separated. The temporary decrease in I_S occurring in the first hour, with a consequent increase in I_A (see expanded plot in Fig. 3), can be related to the stabilization of the electrodes potentials after the connection of the sample in the SCMFC (of course the extensive corrosion occurring on the metal is changing its chemical composition). In the first part of the test, lasting approximately the first 6 hours, the mild steel sample remains the preferential anode of the cell and extensive corrosion occurs on its surface. Because of this, the conductivity of the sample metallic surface progressively decreased as well as the activity of bacteria on it. With the reduction of the sample current (occurring after 6 hours from the beginning of the test), the quantity of electrons provided by the cell anode increases again, leading to the last step of the test when, as the metal surface is completely covered by a corrosion products layer mainly composed of oxides and sulphides, micro-organisms are no longer able either to induce corrosion on it or to supply electrons derived from oxidation of acetate present in the solution. Thus, the fuel cell gets back to its normal operation, with current flowing almost only between anode and cathode. Fig. 4 shows the appearance of sample surface after the test, with a uniform biofilm coverage and evidence of corrosion on the metal (grain boundaries are clearly visible).

After the preliminary measurements carried out on the

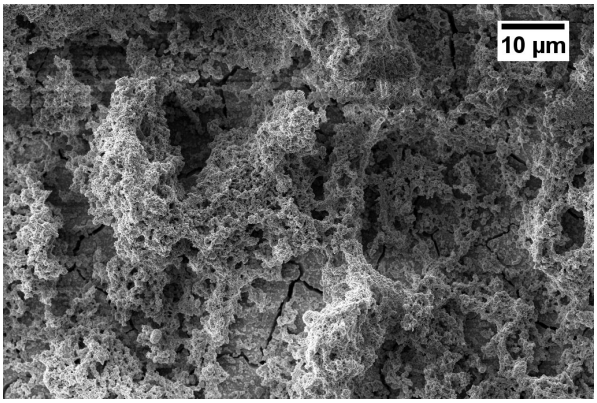

Fig. 4. FESEM image of the mild steel surface after 1 day of immersion in the operating SCMFC. The test results are shown in fig. 3

mild steel samples, a configuration with anode an cathode kept at about the same voltage was chosen; therefore, R_C and R_A were selected to have a lower nominal value of 22 Ω to increase the bacteria activity even though at the expense of the SCMFC output power. Since the measuring system is designed to work with samples characterized by good corrosion resistance, low I_S values are expected so that an R_S resistance with nominal value of 100 Ω has been selected. These resistors were measured with an uncertainty of 0.03% by using a calibrated HP34401. By using carbon-films resistors, a thermal coefficient of about ± 350 ppm/°C can be expected that turns out in a thermal related uncertainty of less than 0.2% for a temperature change of ± 5 °C, which reasonably is the maximum expected change.

The reduced value of R_C and R_A leads to a slightly higher current compared to the value measured on the mild steel sample, which anyway is expected to remain of the order of 1 mA or below. In this condition, the maximum voltage difference between anode and cathode is of the order of 40 mV, which does not exceed about 10% of the open circuit voltage difference expected (i.e. 400 mV).

The voltage drops on both R_A and R_C, measured by the USB6216, are of the order of 20 mV which allows employing the USB6216 input range of ± 200 mV without the need of external amplifiers therefore having the possibility of working without external power supply. Since the USB6216 has a maximum stated uncertainty lower than 90 μV with an input range of 200 mV, this turns out in an uncertainty for anode and cathode currents, whose values are expected to be of the order of 1 mA, of about 0.45%.

Since the USB6216 has a maximum sampling rate of 400 kHz, all measurement are performed by simultaneously sampling all signals at 40 kHz and taking 8000 samples per channel; the measurement therefore requires only 200 ms, and consequently the effect of the power supply noise is negligible. The data averaging also reduces the ADC noise contribution so that the final expected uncertainty on each value is lower than the stated value.

In these experimental conditions therefore an uncertainty lower than 1% is obtained for anode and cathode current values, which are higher then 600 μA; same uncertainty is

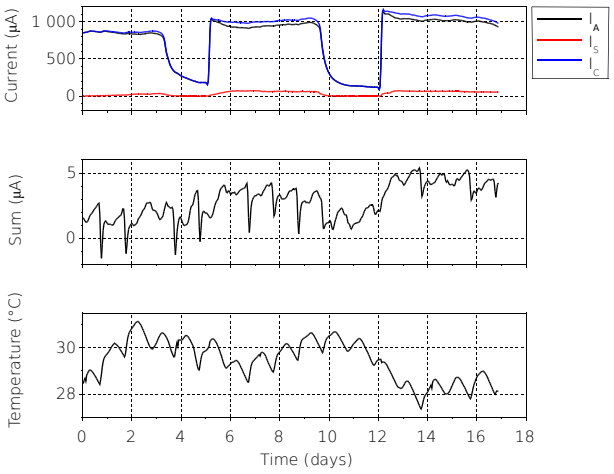

Fig. 5. Current evolution measured in microbial fuel cell during a test performed on a stainless steel sample for 17 days. The I_A, I_C and I_S trends, the current sum and the temperature trends as a function of time are shown. The current values increase after any addition of acetate.

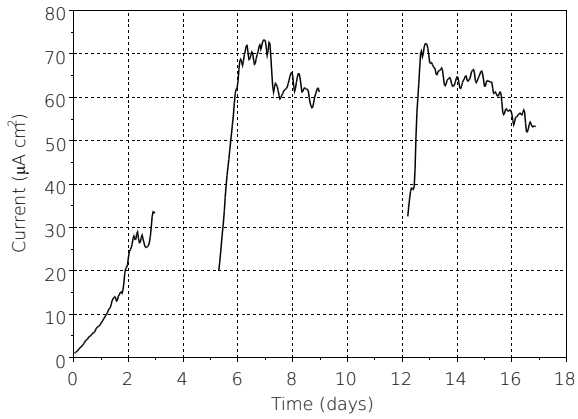

Fig. 6. I_S trend as a function of time recorded in the same test of Fig. 5; the current values are normalized to the surface area of 1 cm^2. I_S increases after any addition of acetate highlighting the bacteria activity on the sample surface.

obtained also for the sample current which is about 125 μA.

A check of the correct system operation can be easily obtained by observing the current sum which has to be zero by design. By considering anode and cathode current the most important part of the sum to obtain an easy uncertainty estimation, a maximum sum of less then 2% of the current can be expected for currents of the order of 1 mA, i.e. a maximum sum current lower than 20 μA is expected.

The temperature is measured by using a simple LM35 temperature sensor connected to a dedicated input channel set to an input voltage range of 1 V. The temperature uncertainty for temperatures in the range 25 °C to 35 °C can be expected to be of the order of 0.5 °C.

III. Experimental Results

In order to validate the measuring approach, some microbial corrosion tests were performed on both carbon steel and stainless steel (AISI 304) samples immersed in the SCMFC.

Carbon steel samples were already analysed [20] and are characterized by a quite low corrosion resistance and therefore by a sample current which immediately increases due to the bacteria colonization, as shown in Fig. 3. Therefore, repeating the tests on materials more resistant to corrosion and commonly used for this applications is extremely important.

An example of the obtained results for stainless steel is shown in Fig. 5 where data from about three weeks are reported. All tests were performed inside a closed chamber to avoid fast temperature changes and keep the system within the desired temperature range. The normal circadian cycle is attenuated but still visible and does not influence the results of the experiment. The temperature was monitored in-continuum to identify possible variations in measured currents due to temperature changes. At the beginning of the test, acetate is added in the electrolytic solution of the fuel cell reaching a concentration of about 3 $\mathrm{g/L}$.

When the stainless steel is immersed into the cell and connected to the measuring system, the cell remains almost unperturbed and keeps its normal working conditions. The current I_S from the sample remains rather small confirming the bacterial electrical activity on the steel is initially negligible as the stainless steel has a good corrosion resistance. The bacteria in the fuel cell degrade the acetate in about one week, after which the anode to cathode current starts decreasing as expected. At this point a new acetate addition is performed to restore the initial concentration. The addition is immediately followed by a current increase as the bacteria start to oxidize the acetate.

Fig. 6 shows an expansion of the I_S current on the stainless steel sample. This current is correlated to the activity of bacteria that progressively colonize the metal surface and start providing electrons not only to the carbon anode but to the sample too. Thus, the measured current sums two contributions due to micro-organisms: oxidation of the metal (that dissolves in the solution) and bacteria metabolism, related to the oxidation of the acetate, which is the fuel inside the cell.

As it can be seen, the value of sample current immediately starts slowly increasing during the first days due to the bacteria activity and then, after about one week it stabilizes, indicating that the bacteria have colonized the surface. An additional evidence that the measured current is correlated to bacteria activity is given by its dramatic decrease when acetate is consumed, as the bacteria stop providing electrons to the electrode. Similar current values and trends were obtained on other stainless steel samples even though the rate of current increase depends on the micro-climate conditions in the cells, which are usually not completely known and controlled in practice.

Fig. 5 also shows the current sum, which as expected remains always below ± 20 μA and which shows a correlation with the temperature, as expected since the resistors have a not negligible thermal coefficient. The temperature during all the tests remains between 27 °C and 32 °C.

IV. Comparison with Traditional Immersion Test

The obtained test results highlight how the current I_s from the sample seems to be representative of the biofilm growth on

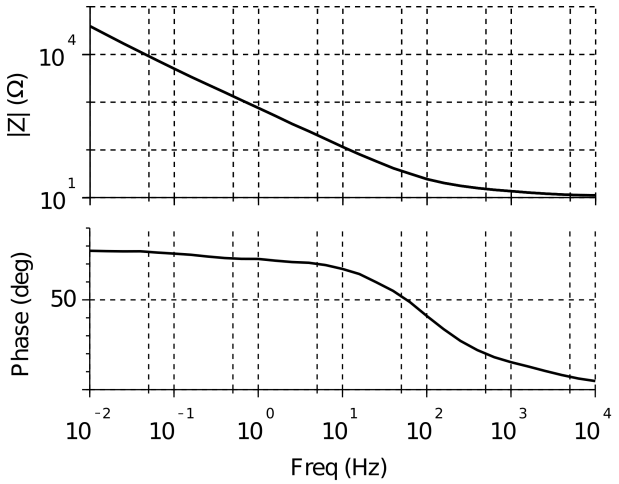

Fig. 7. Bode plots recorded on the AISI304 stainless steel sample immersed in the electrolytic solution containing the bacteria inoculum for three weeks.

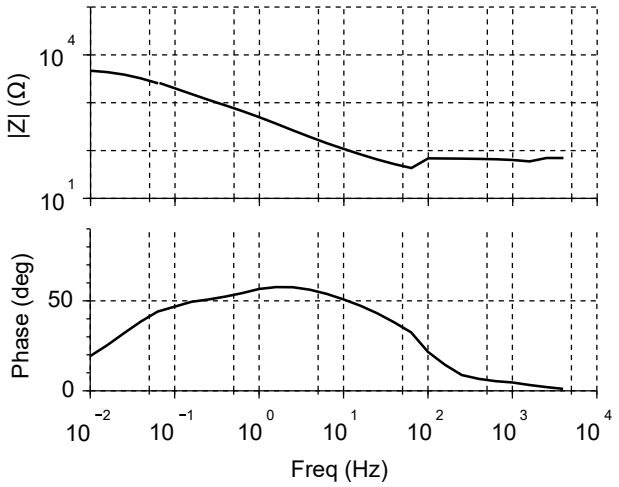

Fig. 8. Bode plots recorded on the AISI304 stainless steel sample exposed in the operating fuel cell for 3 weeks.

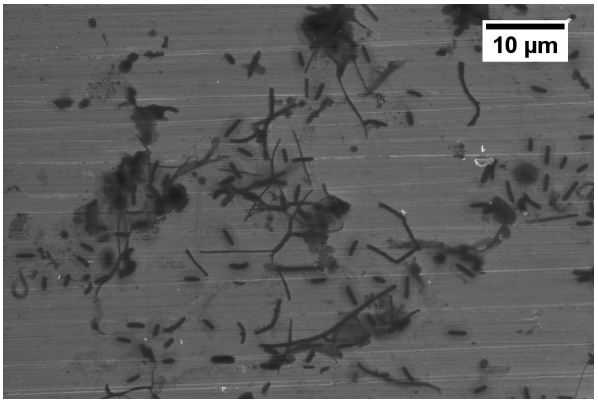

Fig. 9. FESEM images of the AISI304 stainless steel sample immersed in the electrolytic solution containing the bacteria inoculum for three weeks.

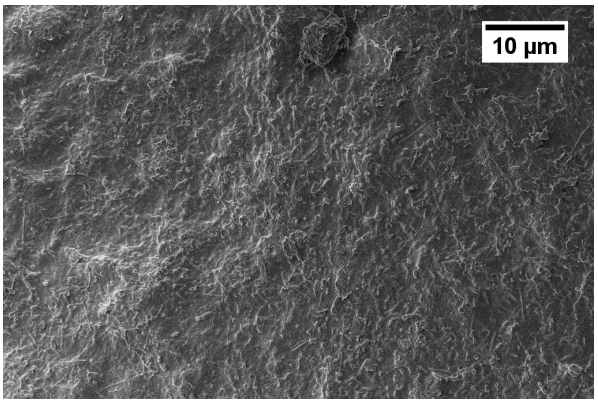

Fig. 10. FESEM images of the AISI304 stainless steel sample exposed in the operating fuel cell for three weeks.

the sample and consequently of the corrosion on the surface, enabling researchers to easily compare microbial corrosion resistance of different materials in a simple and direct way.

To confirm this correlation, the results obtained through the proposed measuring system have been compared to those of a standard immersion test where the polarization effect, due to the connection of sample inside the fuel cell, is not present.

The immersion tests were carried out in parallel with the SCMFC test, using the same electrolytic solution, wastewater, in the same temperature range of 30 ± 3 °C and adding acetate at the same time interval even though the bacteria activity in the solution is not monitored.

Results have been compared in terms of corrosion behavior of the metal assessed by means of Electrochemical Impedance Spectroscopy (EIS), as commonly done in corrosion tests [21]–[23]. This technique has been preferred to other possible electrochemical measurement, as it is non-destructive and does not alter the corrosion process occurring on the material. EIS measurements were performed on both samples after three weeks test by using an Ivium CompactStat, by applying a sinusoidal signal with amplitude 10 mV in the frequency range 0.01 Hz to 100 kHz and acquiring 5 points per frequency decade. A silver chloride electrode was used as reference electrode and a platinum wire was used as counter electrode.

The morphological characterization of the metallic surfaces was performed by means of Field Emission Scanning Electron Microscopy (FESEM Supra 40 by Zeiss) collecting the images at 5 kV with a 20 μm aperture.

EIS spectra are presented in Fig. 7 and Fig. 8 as Bode diagrams to allow the reader to easily observe the spectrum trends which span an amplitude range of more than three orders of magnitude. The plots show a more stable condition for the sample that underwent a simple immersion test, for which impedance modulus reaches values close to 10^5 $\Omega \cdot \mathrm{cm}^2$ and the phase reaches almost $80°$ (at low frequencies), showing a good corrosion resistance still after 20 days of immersion. This result is consistent with the good corrosion resistance of AISI 304 steel in a solution containing bacteria. As far as the SCMFC test sample is concerned, a different condition could be highlighted. Actually, the test had been more aggressive for the metal, which exhibits an impedance modulus one order of magnitude lower than the other sample (about 10^4 $\Omega \cdot \mathrm{cm}^2$ at low frequencies). The phase reaches a maximum value of $60°$,

indicating a less protective nature of the superficial layer.

Observing the samples at FESEM after the two tests, it is possible to compare the different bacteria sample colonization (see Fig. 9 and Fig. 10). Images show a completely different biofilm growth between the two samples. The sample tested inside the fuel cell exhibits a continuous biofilm coverage, which conceals the metal. The presence of the air-breathing cathode, where reduction reactions are able to exploit the electrons coming from oxidation of acetate and metal, favours the colonization of the electrode surface by bacteria. On the other hand, colonization by bacteria appears at a less advanced stage for the sample that underwent a simple immersion test. Micro-organisms are present on the surface, but only discontinuously, as they have not developed a compact biofilm well adherent to the surface.

Using the SCMFC system allows one to obtain results and information concerning the microbial corrosion resistance of a specific metal in a shorter time just promoting mechanisms that also in a real environment could be possible. Actually, the situation of having a component partially in anaerobic and partially in aerobic condition is fairly common, as an example in the case of a partly submerged pipeline. Thus the sample polarization to a potential intermediate between the anode (anaerobic) one and the cathode (aerobic) one appears justified for an accelerated corrosion test.

Moreover, good agreement can be found between currents I_S measured for different materials during the test in the SCMFC and EIS spectra collected after the test. Actually, alloys with poor corrosion resistance exhibited high I_S values and low modulus of impedance (for the carbon steel samples, values close to $10^2\ \Omega \cdot \mathrm{cm}^2$ at low frequencies); on the other hand, for materials with good corrosion resistance, low I_S values and higher modulus of impedance can be found (such as in the case of the stainless steel sample). As the current flowing from the sample to the cathode is related to metal oxidation as well as to bacteria metabolism, a direct relationship between such current and the corrosion rate can not be established. It is however possible to state that, in this specific test condition, the corrosion current is at most equal to I_S. So a comparison between different materials is possible and, as discussed for EIS measurements, supported also by traditional electrochemical methods.

V. Conclusion

An innovative approach for microbial corrosion testing has been presented. The proposed system, that makes use of a single chamber microbial fuel cell, has been exploited in a comparative study to assess the microbial corrosion behavior of mild steel and stainless steel samples, highlighting of course the different corrosion resistance of the two alloys.

Information gained by the test are manifold. By measuring the current between anode and cathode, it is possible to monitor the bacteria activity so that it is possible to be sure to have enough nutrient concentration to have active bacteria. After sample connection inside the fuel cell, measuring the current between sample and cathode allows users to detect corrosion reactions occurring on metal surface. In the case of a material with poor corrosion resistance, large variations in the current flowing in the fuel cell can be observed, highlighting the corrosion reactions that are in progress on metal surface. On the other hand, when a material with good corrosion resistance is tested inside the cell, the current measured between sample and cathode increases slowly, until it stabilizes. This current monitoring enables to assess the progressive sample surface colonization by bacteria, which form the biofilm, and the corrosion processes ongoing on the sample surface. Even though the bacteria initial concentration is important to define the current increase rate, after the colonization the final value remains similar for materials with comparable corrosion resistance, making the system suitable to discriminate between different materials selecting the one more suitable for a specific application.

The use of single chamber microbial fuel cell allows users to perform tests in conditions similar to the real ones and is faster then in the case of simple immersion test. Actually, the sample polarization obtained in the fuel cell leads to a faster colonization of the metal surface by bacteria.

In addition, by employing the SCFMC a direct measurement of the nutrient concentration is not required since the current monitoring can be used as a direct indicator of the bacteria activity. This permits to avoid employing costly instrumentation and opens to the possibility of replicating the measuring system to several microbial cells to study the corrosion resistance of different materials at a minimum cost.

This new technique can be considered as an additional tool for researchers in microbial corrosion field. As previously discussed, test conditions are more aggressive than a simple immersion test and many important information can be easily gathered from currents flowing in the SCMFC. Compared to the Dual Cell technique, the proposed methodology has a simpler experimental setup. Moreover, information that can be derived from the two experiments are slightly different. Actually, in the SCMFC, test conditions are strictly anaerobic, allowing to study more in depth this situation. On the other hand, the Dual Cell technique is more focused on the comparison between material behaviour in sterile conditions or in an environment containing bacteria.

Advantages of this new proposed technique are then related to the test simplification in the part specifically related to biology, because bacteria cultures are not needed, as the solution can be taken directly from the environment. Eventually, performing experiments with different bacteria strains allows one to obtain results more adherent to those found in each real specific condition.

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