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Influence of *Aspergillus fumigatus* on corrosion behaviour of mild steel and aluminium

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ABSTRACT

Growth of fungi and indeed microorganisms on metal surfaces can initiate, facilitate and accelerate corrosion reactions, altering the composition and integrity of such metal without changing its electrochemical nature. Studies on fungal influenced corrosion (FIC) of mild steel (MS) and aluminium (Al) in the presence of *Aspergillus fumigatus* were carried out using gravimetric techniques. Mild steel (C-0.30%, Si-0.30%, Mn-0.30%, P-0.045%, S-0.050%, Cr-0.064%, Cu-0.040%, Ti-0.04% and balance Fe) and aluminium (Al >95.5%) plates, 2×2×0.14 cm and 3×1.5×0.1 cm in size respectively, were contaminated with the fungi in Petri dishes with nutrient medium imitating organic pollution. The results obtained reveal that the metals reacted differently to the impact of *A. fumigatus*. The influence was dependent on the capacity of fungi to grow and develop on the metal surface, and produce metabolites that stimulate changes in polarization resistance and destruction of the metal surfaces. The potentiodynamic polarization profile in the presence of *A. fumigatus* showed a rise in corrosion current density (I_{corr}) from 187.95 and 153.5 μA/cm^2 (in the absence of the fungi) to 279.4 and 201.2 μA/cm^2 (in the presence of the fungi) for mild steel and aluminium, respectively. The gravimetric analysis further revealed that the corrosion and weight loss of the metals increased with time.

INTRODUCTION

Metals are widely used in industrial applications due to their strength and structural integrity. Most metals are normally coated for corrosion protection while cathodic protection may also be used. For selected applications, galvanization (zinc coating) may be used to protect steels in atmospheric environments (Muthukumar et al., 2003). Bituminous coal tar and asphalt dip coatings (Akpabio et al., 2011) are often used on the exterior of buried pipelines and tanks while polymeric coatings are used for atmospheric and water environments. However, biofilm tends to form at flaws in coating surfaces. Furthermore, acid producing microorganisms have been found to dissolve zinc and polymeric coatings (Mansfield and Little, 1991).

Most laboratory and field studies on MIC have focused mostly on bacterial involvement; however, other single-cell organisms including fungi can influence corrosion processes. Fungi have been implicated in the corrosion of many metals and their alloy used in fabrication and construction of buildings. Fungal influenced corrosion (FIC) has been reported for some metals and aluminum alloys exposed to hydrocarbon fuels during transport or storage (Videla, 2002). De Mele et al. (1979) reported that corrosivity increased with contact time due to accumulation of metabolites under fungal colonies attached to metal surfaces. De Meybaum and de Schiapparelli (1980) demonstrated that the metabolic products of fungi enhanced aqueous phase aggressiveness even after the life cycle of *Cladosporium* sp. was completed. Rosales (1985) also demonstrated metal ion binding by fungi mycelia, resulting in metal ion

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concentration cells on aluminium surfaces.

Aspergillus fumigatus is a fungus of the genus *Aspergillus*. It is widespread in nature and is typically found in soil and decaying matter such as compost heaps where it plays an essential role in carbon and nitrogen recycling. The fungus is capable of growth at 37°C or 99°F and can grow at temperature up to 50°C with conidia surviving at 70°C. *A. fumigatus* grown on some building materials can produce gentotoxic and cytotoxic mycotoxins such as gliotoxin (Nieminen et al., 2002). The organism mostly acquires their nutrients from external environment in order to survive. Examples of nutrient uptake include that of metals, nitrogen and macromolecules such as peptides (Dagenais and Keller 2009). *A. fumigatus* has two mechanisms for the uptake of iron which include reductive iron acquisition and siderophore-mediated (Haas, 2003). Reduction iron acquisition includes conversion of iron from the ferric (Fe^{+3}) to the ferrous (Fe^{+2}) state and subsequent uptake via FtrA, an iron permease. The life cycle of *A. fumigatus* consists of two phases: a hyphal growth phase and a reproductive (sporulation) phase. The switch between growth and reproductive phases of these fungi is regulated in part by secondary metabolite production (Tao and Yu, 2011). The ability of fungi to undergo oligotrophic growth, their explorative filamentous growth habit, flexible growth strategies and most importantly, resistance to extreme environmental factors including metal toxicity make them successful colonizers of metals (Lugauskas et al., 2009). The aim of this study was to study the influence of *A. fumigatus* isolated from corroding pipeline on the corrosion behaviour of mild steel and aluminium.

MATERIALS AND METHODS

Metal coupons of mild steel with weight percentage composition as follows C-0.03; Si-0.30; P-0.045, S-0.05, Cr-0-064; Cu-0-040; Ti-0.30 and the balance Fe and aluminium (Al>99.5) were used in the study. The metals were cut into coupons of specific dimensions 2×2×0.14 cm for mild steel and 3×1.5×0.1 cm for aluminium. The exposed metal plates were wet polished with silicon carbide abrasive paper (from grade No 400-1000), rinsed with distilled water, dried in acetone and warm air, weighed and stored in moisture free desiccators prior to use (Oguzie et al., 2013).

The fungal sample used in this study was collected from corroded pipelines within a National Petroleum Cooperation Depot and from aluminium roofing sheets. Corroded parts of the metals including corrosion products were aseptically collected in sterile bottle using sterile spatula. The rust layers were scrapped and diluted (tenfold serial dilution) with distilled water, 1 mL of the fifth serial dilution was collected and inoculated on potato dextrose agar PDA (Oxoid) plates supplemented with antibiotics streptomycin (5 µg/mL). Each morphological discrete fungal colony was then sub-cultured and purified by repeated streaking on PDA plates. Pure cultures were then preserved on PDA slants in Bijou bottles and stored at 4°C in a refrigerator for further studies. Fungal isolate was characterized and identified based on their morphological characteristics and microscopic analysis using taxonomic guides and standard procedures as outlined by Hussian et al. (2011).

The contact of the metals with the fungi was investigated. Metal coupons were placed in Petri dishes filled with a sterile agar medium of malt extract supplied with Streptomycin (5 µg/mL). The medium with the metal coupons was then inoculated with *A. fumigatus*. Two controls were provided. In control one C1 metal was exposed to common conditions and not contaminated with fungi. In control two C2 metal was placed in PDA medium but not inoculated with fungi. Medium with metal was incubated at 27°C. The entire experiment were uniformly prepared in triplicate, labeled accordingly and inserted the same day. The experiment was observed for a period of 60 days at 10 days intervals. The intensity of fungal growth and metal oxidation as well as surface changes (Lugauskas et al., 2009) were evaluated after 30 and 60 days. The extent of the fungal growth and metal deterioration was assessed with naked eyes and by light microscope in accordance with the scheme [EM ISO 10289: 1999] (Lugauskas et al., 2008):

- No fungi growth observed on specimens under a light microscope – 1 point;
- Mycelium with branched hyhae and possibly sporulation, visible under light microscope – 2 points;
- Growth of fungi, spare but visible to the naked eye under the light microscope, sporulation clearly visible – 3 points;
- Growth of fungi clearly evident but covering <25% of the tested surface – 4 points;
- Heavy growth of fungi visible to the naked eye and covering >25% of the surface 5 – points (Lugauskas et al., 2009).

Morphological changes on the metals were evaluated using an optical microscope with a CCD camera at about 45× magnification and the magnitude of marker was 10 µm per 1 cm of the photograph.

Gravimetric experiments

Gravimetric experiments were conducted on the metals. To determine the weight loss with respect to time, the coupons were retrieved every 10 days, washed with distilled water, dried and weighed. The weight loss was taken to be the difference between the weight of the

Table 1. Results of the exposure of *A. fumigatus* to mild steel and aluminum metals after 30 and 60 days exposure.

Fungal species	Changes on metal surfaces
Mild steel after 30 days of exposure to fungi *A. fumigatus*	Fungi covers almost the whole surface of metals.
Aluminium after 30 days of exposure to fungi *A. fumigatus*	Fungi covered all the edges of metal where mycelia spread over metal surfaces.
Mild steel after 60 days of exposure to fungi *A. fumigatus*	Fungi grew intensively on the edges of metals with thin network of mycelia and some discrete colonies scattered over the surfaces.
Aluminium after 60 days of exposure to fungi *A. fumigatus*	Fungi grew intensely on the edges of metals from where mycelia and conidia spread over the surfaces like cobwebs.

coupons at a given time and its initial weight. All tests were run in triplicate and the data showed good reproducibility. Average values for each experiment were obtained and used in subsequent calculations. The weight loss (WL) with respect to time was quantified by comparing the initial weight (WI) and final weight (WF) respectively as follows:

$$WL = WI - WF \qquad (1)$$

The corrosion rate (CR) was determined as follows:

$$CR = \frac{k\Delta M}{A\rho t} \qquad (2)$$

Where k – represents corrosion rate constant (143,700 mpy); A – total exposed surface area of coupon (cm^2); ρ – density of metal coupon (g/cm^3); while ΔM and t – stands for weight loss of coupon (g); and t – time (days) respectively.

Electrochemical measurements

The potentiodynamic polarization test was carried out in a standard three-electrode glass cell of 500 mL capacity using Electrochemical System workstation (PAR 263). A graphite rod served as counter electrode and, a saturated calomel electrode (SCE) was used as reference electrodes. A mild steel and aluminum specimen of 1 cm^2 dimension were used as working electrode. Electrochemical measurements were carried out at 30±1°C, using standard procedures as outlined by Oguzie et al. (2013), in aerated solutions at the end of 1800s of immersion, which allowed the open circuit potential (OCP) values to attain steady state. The polarization (PDP) experiments were then conducted at a scan rate of 0.333 mV/s. The potential range employed was -250 to +300 mV versus corrosion potential. Powersuite software was used in analyzing the polarization data.

RESULTS AND DISCUSSION

The characterization and identification results showed prominently the presence of *A. fumigatus*. Akpan and Mohammed (2015) reported the isolation of *A. fumigatus* from a corroded pipeline. Lugauskas et al. (2009) reported that the most frequent saprotrophic micro fungi isolated from most metal surfaces are species from the genus *Aspergillius*, *Penicillium, Scopulariopsis, Paecilomyces*, *Trichoderma*, *Fusarium*, *Rhizomucor*, *Rhizopus*, *Mucor, Alternaria*. Bento et al. (1996) also isolated *A. fumigatus* from diesel storage tank. Little et al. (1992) isolated *A. fumigatus* from condemned aluminium corroding aircraft component parts. They observed that *A. fumigatus* together with other fungal species isolated promoted the MIC of aluminium AL2024-T3 alloy used in the construction of aircraft.

Fungal interaction with metal surface: The data presented in Table 1 showed that *A. fumigatus* was able to grow on the surface of mild steel and aluminium at various degrees after 30 and 60 days exposure. Table 2 shows the relationship between the intensity of fungal growth, metal oxidation and surface changes after 60 days exposure to the influence of *A. fumigatus*. Microbial corrosion and biodeterioration are directly related to the presence of biofouling deposits on metal surfaces mediated by microorganisms adhered to metal surfaces. As microorganisms like fungi adhere to metal surfaces by means of their physiological activities, they are able to change electrochemical conditions on the metal in the most corrosion relevant way (Lugauskas et al., 2009). Additionally, fungi produce carbon dioxide which reacts with water to form carbonic acid. The results of the response of mild steel and aluminum to the corrosion behaviour of *A. fumigatus* showed significant prove of metal oxidation and surface changes. *A. fumigatus* grew prominently on the surface of mild steel throughout the period of exposure with conidia scattered over the whole surfaces. Lugauska et al. (2009) reported the growth of *Aspergillius* sp. on metal plates with colonies formed and conidia scattered over the metal plate surfaces. The

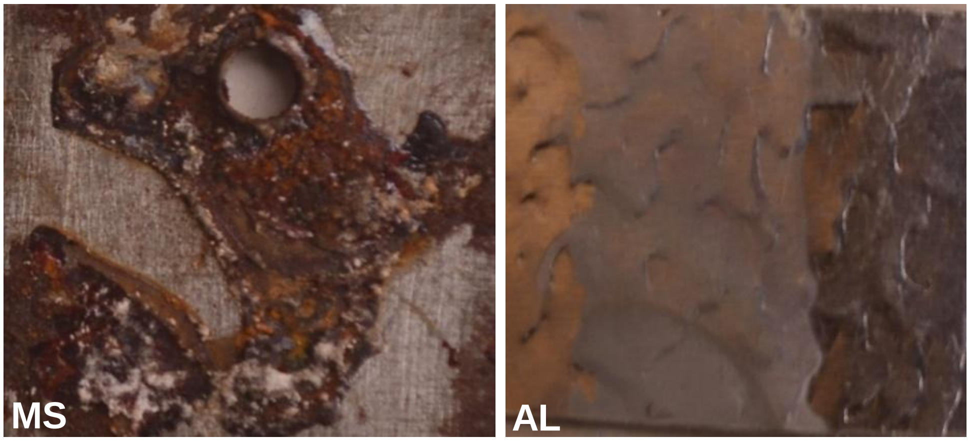

Figure 1. Microscopic view of changes in mild steel and aluminium after 60 days exposure to *A. fumigatus*.
MS, Mild steel; Al-Aluminium.

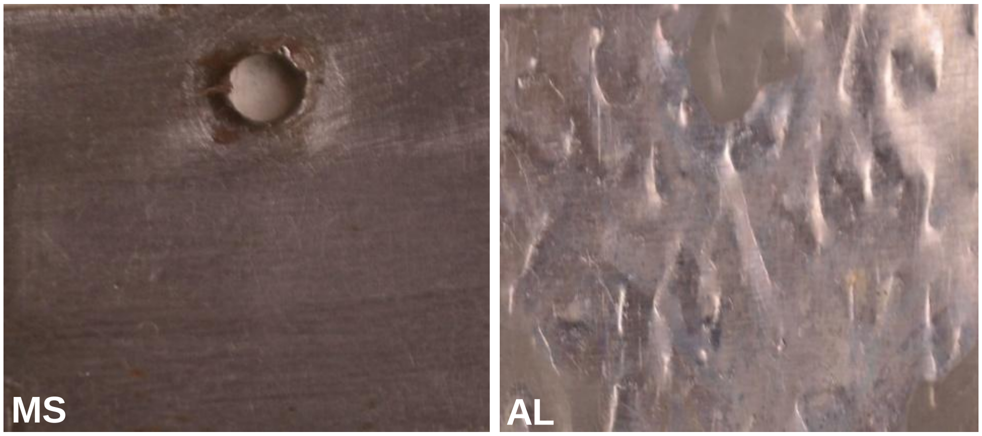

Figure 2. Metals not exposed (control) to the influence of *A. fumigatus*.
MS, Mild steel; Al, aluminium.

Table 2. Relationship between the intensity of fungal growth, metal oxidation and surface changes after 60 days exposure.

Fungal species	Changes on metal surfaces	Intensity of deterioration on point 1-5 scale
Mild Steel *A. fumigatus*	Metal visibly and heavily corroded with coarse corrosion nidi over the surfaces and edges with visible pits.	4
Aluminium *A. fumigatus*	Visible colour change on the surfaces the metals with dark corrosion spots.	3

influence of *A. fumigatus* on the mild steel after 60 days is evident with visible deterioration and heavily corroded spots on the surfaces with visible pits. The influence of the fungi on aluminium was evident with dark corrosion spots on the surfaces and rough edges.

The study of the relationship between the intensity of fungal growth, metal oxidation and surface changes after 60 days is shown on Figures 1 and 2. Prominent

Table 3. The influence of *A. fumigatus* on the corrosion behaviour of mild steel.

Fungi	**Metal density (gcm^{-3})**	**Initial weight (g)**	**Final weight (g)**	**Δ weight (g)**	**Surface area (cm^2)**	**Exposed time (Days)**	**Corrosion rate CR (mpy)**
A. fumigatus	7.9	8.717	8.716	0.001	9.12	10	0.19
	7.9	9.080	9.075	0.005	9.12	20	0.50
	7.9	8.937	8.921	0.016	9.12	30	1.06
	7.9	8.464	8.434	0.030	9.12	40	1.50
	7.9	8.755	8.705	0.050	9.12	50	2.00
	7.9	8.759	8.679	0.080	9.12	60	2.60

Table 4. The influence of *A. fumigatus* on the corrosion behaviour of aluminum.

Fungi	**Metal density (gcm^{-3})**	**Initial weight (g)**	**Final weight (g)**	**Δ weight (g)**	**Surface area (cm^2)**	**Exposed time (Days)**	**Corrosion rate CR (mpy)**
A. fumigatus	2.70	1.615	1.612	0.001	9.9	10	0.61
	2.70	1.578	1.575	0.003	9.9	20	0.80
	2.7	1.578	1.572	0.006	9.9	30	1.07
	2.7	1.658	1.649	0.009	9.9	40	1.20
	2.7	1.705	1.690	0.015	9.9	50	1.61
	2.7	1.615	1.581	0.034	9.9	60	2.20

corrosion nidi were seen on the surfaces of the mild steel metal with more of these corrosion defects centered on the edges. On the surfaces of aluminum, corrosion spots and color changes were observed on the edges. Lugauskas et al. (2008) reported that the results of the studies performed under laboratory conditions indicated that *Acremonium* sp. contaminated aluminum metals. According to them, this fungus produces fusidic acid and its sodium salt fusidin which affected the metal surfaces. Videla (2001) also stated that acids produced by fungi are damaging to metals and other materials. The surfaces of mild steel were visibly and heavily corroded with coarse corrosion nidi over the surfaces and edges as a result of the growth of *A. fumigatus* on the metal surfaces. On the surface of aluminium, there were visible color changes with dark corrosion spot. It is therefore possible that the deteriorations and changes on the metal surfaces might have been caused by the fungi.

The gravimetric results of the influence of *A. fumigatus* on the corrosion behaviour of mild steel and aluminium are shown on Table 3 and 4. The results showed that the growth of *A. fumigatus* on the mild steel increased the corrosion of the metal as shown by the increase in the corrosion rate from 0.19 mpy after 10 days to 2.6 mpy after 60 days. There was also a corresponding increase in the weight loss during the period. The corrosion rate of aluminium also increased from 0.61 g after 10 days of exposure to *A. fumigatus* to 2.20 g after 60 days (Figures 3, 4, 5 and 6). It can be observed that corrosion rate increased with increase in time. This was very pronounced from the 30th day of exposure to the fungi and then continued progressively for the rest of the period. This observation is typical of a metal that demonstrates passivity effects. These results suggest that the corrosion rate might have been influenced by the presence of fungi on the surface of the metals. The corrosion rates may also have been enhanced due to the creation of oxygen concentration or differential aeration cell caused by the patchy growth and distribution of fungal colonies and their metabolites (Hamilton and Lee, 1995). Juzeliunas et al. (2007) observed that the overgrowth of metallic surfaces with fungus mycelia was closely related to electrochemical processes. It is also possible that since corrosion is an electrochemical process, the increase in corrosion rate observed could have been due to fungal growth on the metals. To further support this results, Stokes and Lindsay (1979) stated that the electrical characteristics of steel and aluminium can be worsened by growth and attachment of some species of fungi belonging to the genera *Aspergillius* and *Penicillium*. Similar observations have been reported by Agerry and Salam (2016), Akpan et al. (2013), Beech (2002), Biljana (2012) and de Mele et al. (1979).

Electrochemical data

The kinetics of the anodic and cathodic reactions

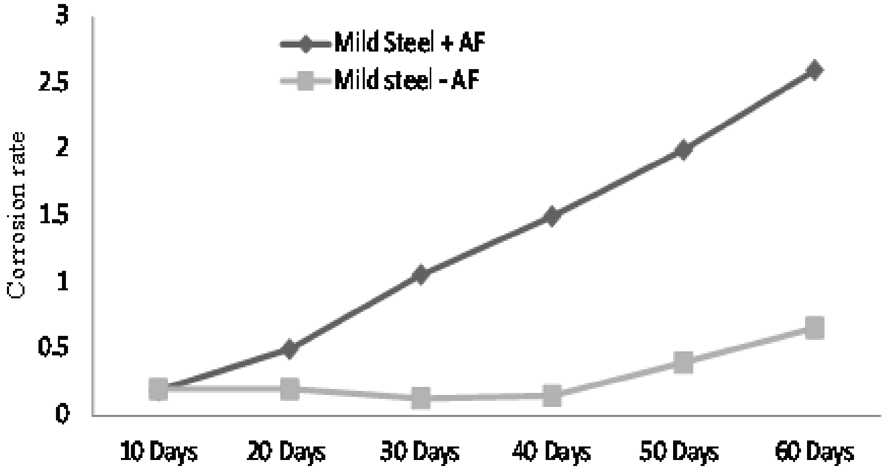

Figure 3. Corrosion rate of mild steel exposed to influence of *A. fumigatus* (AF).

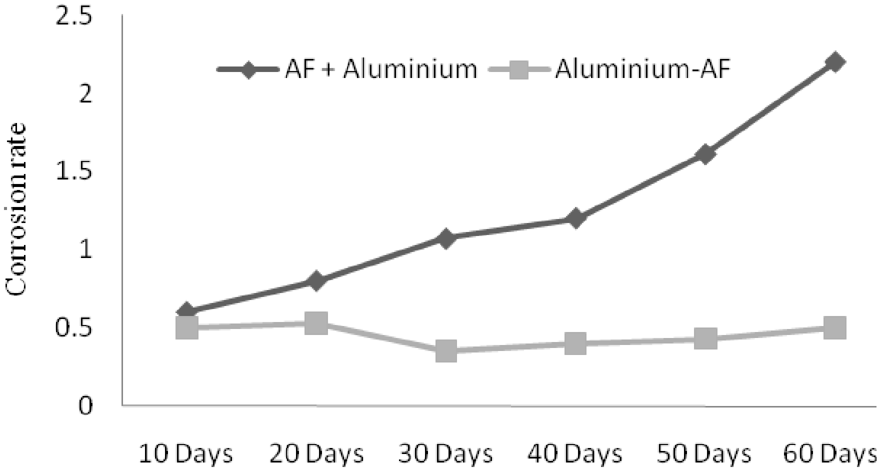

Figure 4. Corrosion rate of aluminium exposed to influence of *A. fumigatus* (AF).

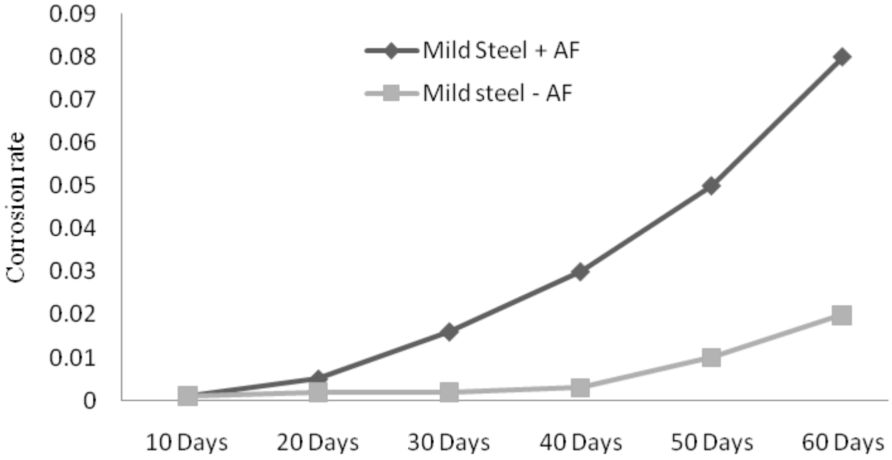

Figure 5. Weight loss of mild steel exposed to the influence of *A. fumigatus.* (AF).

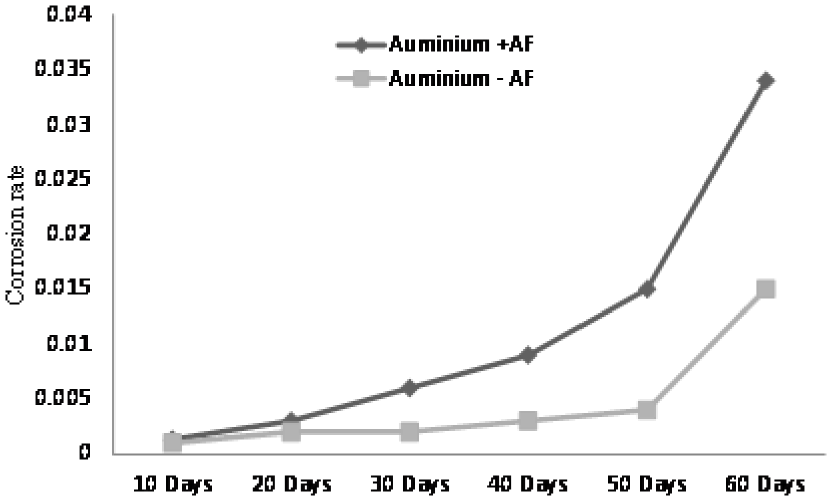

Figure 6. Weight loss of aluminium exposed to the influence of *A. fumigatus* (AF).

Table 5. Polarization data for mild steel in the presence of *A .fumigatus.*

Fungi	I_{corr} (μA/cm^2)	E_{corr} mV Vs SEC	b_a	b_c
A. fumigatus MS2	279.4	−485.4	115.1	75.1
Control MS4	187.9	−491.8	105.3	69.2

Table 6. Polarization data for aluminium in the presence of *A. fumigatus*.

Fungi	I_{corr} (μA/cm^2)	E_{corr} mV Vs SEC	b_a	b_c
A. fumigatus AL2	201.2	−796.4	97.6	109.8
Control AL4	153.5	−701.6	89.5	100.3

occurring on the mild steel and aluminium metals in the presence and absence of *A. fumigatus* was studied using potentiodynamic polarization measurement technique. The results of the potentiodynamic polarization test and the corresponding polarization data are presented in Table 5 and 6. From the study, the corrosion current density (I_{corr}) of mild steel increased from 187.94 μA/cm^2 (in the absence of fungi MS4) to 279.4 μA/cm^2 in the presence of *A. fumigatus* (Table 5). Similarly, there was a rise in corrosion current density of aluminium when exposed to aluminium (201.2 μA/cm^2) compared to the absence of fungi (153.5 μA/cm^2). Figures 7 and 8 show typical potentiodynamic polarization curves of mild steel and aluminium in the presence of *A. fumigatus*. The mild steel is seen to exhibit active dissolution with no clear transition to passivation within the studied potential range. Mansfield and Little (1991) used potentiodynamic polarization technique to examine the overall corrosion behaviour of a corrosion system. The authors observed that increase in corrosion current (I_{corr}) density was due to the influence of microorganisms on the rate of the anodic and cathodic reactions. In this study, it can be seen from the results that the rate of metal dissolution or oxidation is proportional to the corrosion current (I_{corr}). This is also in line with the findings of Videla (2000) who stated that corrosion rate is proportional to corrosion current density.

A substantial shift of E_{corr} towards noble values occurred throughout the period of exposure of the mild steel (Table 5) to *A. fumigatus*. The shift to positive potential observed (-485.4 mV/SCE) correlates with the growth of fungi on the mild steel when compared with -491.8 mV/SEC obtained in the absence of fungi. Similar observation was reported by Faisal et al. (2013) in their work with facultative anaerobic *Desulfovibrio* sp. The potential shift clearly supports the findings that activities and growth of microorganism on metal surface enhanced the redox quality of the medium and accelerated the metal dissolution. The positive shifts in E_{corr} also lead to ennoblement which is an indicator for potential corrosion. Ennoblement in microbiologically influenced corrosion

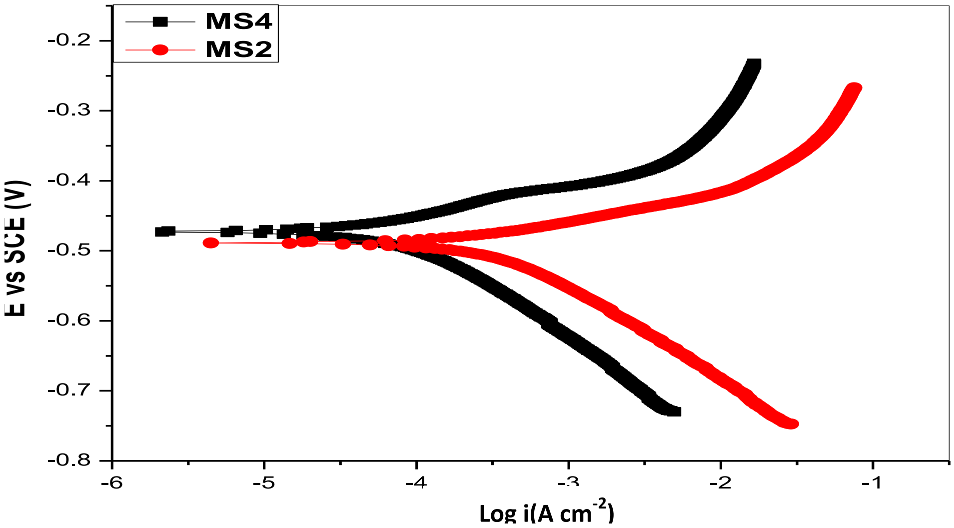

Figure 7. Potentiodynamic polarization curves of mild steel in the absence and presence of *A. fumigatus*.

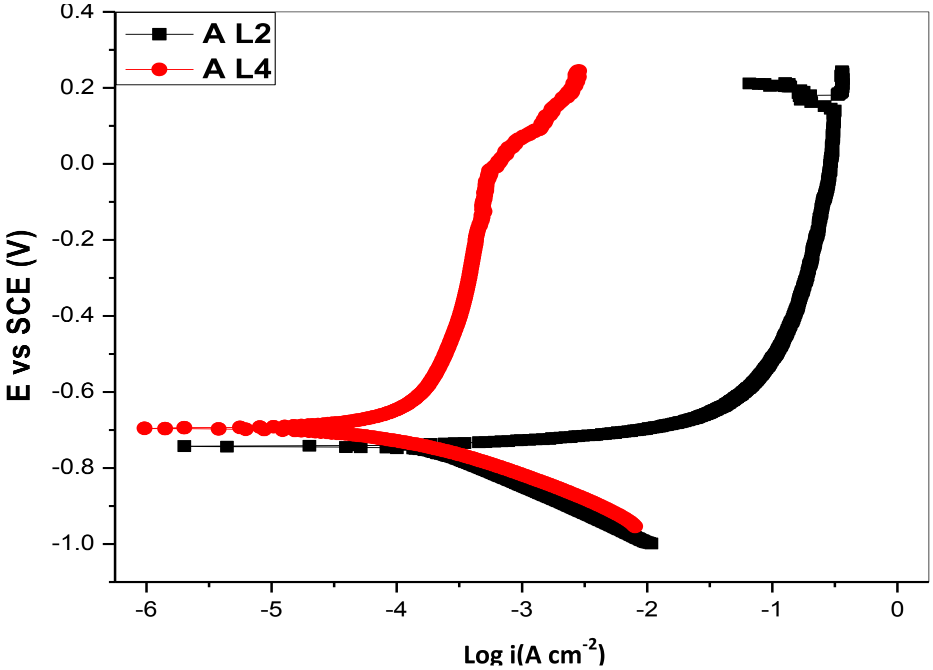

Figure 8. Potentiodynamic polarization curves of aluminium in the absence and presence of *A. fumigatus.*

(MIC) has been acknowledged by different investigators as probably the most notable phenomenon in MIC studies (Faisal et al., 2013; Little et al., 2001; Videla, 2003). It has been attributed to the microbial colonization and biofilm formation which collectively results in organometallic catalysis and acidification of the metal surface which promotes pitting corrosion as was observed on the mild steel in the presence of fungi.

Conclusion

This study shows that mild steel and aluminum metals respond to the effects of *A. fumigatus* depending on the fungal ability to develop on the metal surface and produce metabolites stimulating changes. The gravimetric results indicate that corrosion rate increased with exposed time. The potentiodynamic polarization results from this study collaborate with gravimetric studies. Finally, the results obtained in this study support the hypothesis that the attachment and growth of fungi on the surface of metal can influence their corrosion.

Authors' contribution statement

The first author conceived the idea, performed most of the experiments and wrote the manuscript, the other authors designed the experiment layout and edited the manuscript.

Conflict of interest

The authors declare that there is no conflict of interest.

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