Experimental Analysis of Environmental Effects on Corrosion and Degradation of Metals

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Abstract:
Corrosion is a degradation of materials particularly metals due to corrosive environmental reaction between materials. The corrosion resistance of any metallic material depends on the environment to which it is exposed. The environment consists of the entire surrounding in contact with the material. Experimental method was employed for conducting this research. Experiment was carried out in the corrosion laboratory of Defense Engineering College Ethiopia with the objectives of identifying the degree of corrosiveness of the environment and to evaluate the corrosion resistance of different materials. Specimens of various metallic materials of different configurations and dimensions were exposed to various types of environments. Analysis results after exposure of the specimens in the environment showed that strong corrosion environments are acidic environments and common form of corrosion developed were uniform, pitting, crevice, intergranular types respectively. From this it is possible to recommend that further study of environmental effects in metal industries may be carried out to reduce economic lose of the nation and for the purpose of establishing corrosion protection methods in metal industries in Ethiopia.

Key words-*Corrosion, environment, uniform corrosion, pitting corrosion, crevice corrosion, intergranular corrosion, corrosion fatigue.*

1. Introduction

Historically corrosion had known since the early time in different countries. It is possible to say that corrosion has been existed since man knew the first metals. Corrosion can be defined in many ways. The word corrode is derived from the Latin corroders, [1-2] which means “to gnaw to pieces.” The general definition of corrode is to eat into or wear away gradually, as if by gnawing. Many authors agree that corrosion is defined as a chemical or electrochemical reaction between materials, usually a metal, and its environment that produces a deterioration of the material and its properties [1-4]. The reaction and subsequent deterioration of metals when exposed to the environment encompasses a fundamental principle of electrochemistry and metallurgy, known as corrosion [1]. The term corrosion is sometimes also applied to the degradation of plastics, concrete and wood, but generally refers to metals [1-5]. As literature shows [1], iron and steel have a natural tendency to combine with other chemical elements to return to their lowest energy states. In order to return to lower energy states, iron and steel frequently combine with oxygen and water, both of which are present in most natural environments, to form hydrated iron oxides (rust), similar in chemical composition to the original iron ore. Corrosion affects the economic stability of the nation.

Corrosion as a natural phenomenon is part of our everyday life [1-4]. The corrosion reaction produces a new and less desirable material from the original metal and can result in the loss of function of the component or system, a significant problem encountered every day. Practices show that range of corrosion problem is from the rusting of tools and automobiles after many years of service, the failure of volatile materials delivering pipelines and components such as natural gas and environmentally harmful chemicals such as crude oil and hydrochloric acid, and more devastating failures, including plant explosions, bridge failures and aircraft crashes [5-6]. Corrosion has economic effect, health effect, cultural and technological effects of countries. Some studies like the one carried out in the USA in 1976 [9] has shown that the overall annual cost of metallic corrosion to the U.S. economy was $70 billion, or 4.2% of the gross national product. Recent years have seen an increasing use of metal prosthetic devices in the body, such as pins, plates, hip joints, pacemakers, and other implants. New alloys and better techniques of implantation have been developed, but corrosion continues to create problems like, failures through broken connections in pacemakers, inflammation caused by corrosion products in the tissue around implants, and fracture of weight-bearing prosthetic devices [9]. An even more significant problem is corrosion of structures, which can result in severe injuries or even loss of life. As understood from practice and many research works safety is compromised by corrosion contributing to failures of bridges, aircraft, automobiles, gas pipelines etc., the whole complex of metal structures and devices that make up the modern world [7, 9]. Corrosive processes will accelerate the deterioration of precious artifacts by the highly polluted environments that now are well-known in most of the countries of the world. The rate of corrosion depends up on the aggressiveness of the environment and the composition of the metal exposed to the given environment [1-5]. Various environments cause corrosion of metals that weakens its property and application as well as cause economic crisis of the plant and the country at large. Therefore, identifying the type of corrosion environment helps to develop a way to protect corrosion problem. Various corrosion environments have various effects on metallic materials exposed for environments. Rural, industrial urban environments and defense areas environments are basic known corrosion environments, which have different degree of corrosivity. Some countries have allocating large amount of money (about 4 billion USD per year in some countries)[9] for corrosion protection purpose ,which has invested for material selection, design modification, coating, application of inhibitors, routine maintenances, preventive maintenances, training of workers, etc. Maximum of the budget has used up for material selection purpose and have tried to minimize the problem to some degree. In contrary as mentioned though large amount of metallic materials, machineries and equipment have wasted by corrosion, in some countries including Ethiopia as corrosion problem has not taken as a serious problem and no protection mechanism has devised except the traditional painting method.

Thus identifying the corrosion environment based on experimental analysisand establishing effective controlling methods of corrosion is the primary issue to minimize destruction of materials as a result of which to reduce the economic impact of corrosion on the nation

2. Methodology

Most of the research methodologies for corrosion analysis relays on the experimental methodology as this methodology is proper to determine the variables and parameters involved in the process. Thus experimental research method with qualitative and quantitative approaches was used to conduct this research.

About 23 pieces of metallic samples with regular shapes and non-regular shapes were selected randomly as sample. Samples were collected from different old components and sheets were cut from newly purchased material. The reasons of selecting these materials for workwere that these metals are common engineering metals, most mechanical equipment and tools as well as machineries are produced from these materials.

To conduct the research low carbon steel sheet, brass sheet, gray cast iron, brass cartridge, high speed steel, nickel plated aluminum alloy, chrome plated steel bolt, galvanized steel pipe, chrome plated aluminum pieces were used. Laboratory testing,Photographingand measurements of weight specimens were carried out for analysis of environmental effect, to evaluate and select material or protection method for a specific environment in a certain application, to obtain general information about the behavior of certain materials and groups of materials under the main types of corrosion environments and carry out routine control of materials including coatings.

Environments, where the specimens exposed include dust, oil, mild concentrated sodium chloride solution, mild concentrated nitric acid solution, sulphuric acid solution environmental atmosphere, moist soil, tap water, natural mineral water, and kerosene. All specimens were exposed to various environments for a total of 360hrs except 3 mild steel pieces which were exposed to nitric acid and sulfuric acid less than 24 hours and for 24 hours respectively.

Accordingly, the experiment was carried out following the procedure below: Selection test specimens that are representatives of common engineering materials;surface preparation including sanding, polishing using dry rags, sand papers ofno.120,150,180 and 200 respectively;measurement of surface area and thickness of specimen using vernier caliper with an accuracy of 0.01 and 0.05 since thickness measurement is an essential part for corrosion rate evaluation;Degreasing was made first using dry rags and then whipping with moisten rags to avoid dirt and dusts. This has applied for dry coated specimens. For those moisten specimens drying in an oven had taken place and then cleaning with dry clothes; Polishing with fine sand paper was carried out;weighing the specimens was done using Java type analytical balance of accuracy 0.0001g.This helped to determine the weight before corrosion and after corrosion in order to analyze the weight loss of the metal; preparing the environments.Exposure to the environments was done using different vessels made of glass for protection from external links; Inspection of the specimens after exposure, including a preliminary visual inspection with the naked eye, photographing, followed by surface cleaning and polishing for microscopic investigation were carried out.

The corrosion rate, or the rate of material removal [3] as a consequence of the chemical action, is an important corrosion parameter and expressed in terms of corrosion penetration rate (CPR),or the thickness loss of material per unit of time. The formula for this calculation is:

$$\mathrm{CPR} = \frac{\mathrm{KW}}{\mathrm{DAT}} \quad (1)$$

Where W is the weight loss after exposure time T; D and A represent the density and exposed specimen area, respectively, and K=($2.40x10^{6}$), is a constant, that is magnitude depending on the system of units used. From the literatures mil per year (mpy) is the most commonly used corrosion expression and is expressed as:

$$\mathrm{mpy} = \frac{534}{\mathrm{DAT}} \quad (2)$$

In this work, the change of weight of the material was measured for a period of time. The commonly known equation (1) was used for evaluating the corrosion resistance behavior of metal samples involved in the experiment. According to ASTM [3], the corrosion rate is then reported as milligrams per square decimeter per day (MDD).

3. Results and discussion

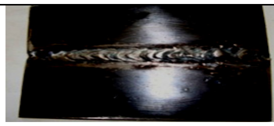
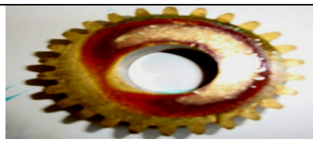
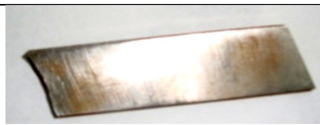
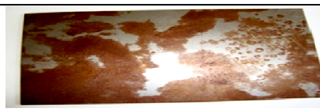
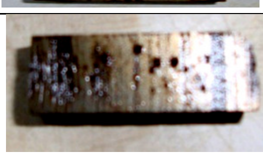
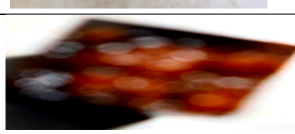
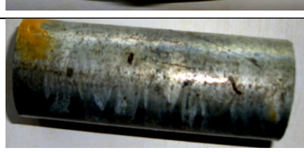
Using the above method and materials experiment was carried out. In table 1 the figures show the corroded specimens obtained after exposure to various environments.

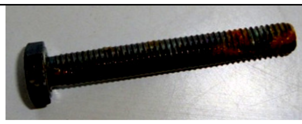
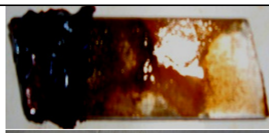
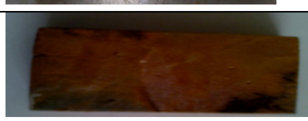
From the experiment uniform,crevice, pitting, de-alloying and intergranular corrosion forms were observed.

From the table it is possible to understand that most of the specimens exposed to different corrosive environments were attacked by uniform corrosion. Pitting is the second corrosion form mostly observed in sodium chloride and tap water. Natural mineral water, atmosphere and sodium chloride solution caused uniform and pitting corrosion.

Table1 Experimental specimens

No	Picture	Material	environment	Corrosion form
1		Cast iron	Oil +dust	Uniform Pitting, crevice
2		Mild steel	NaCl solution	Uniform, pitting
3		Mild steel sheet	Moist soil	uniform
4		Mild steel sheet	Oil +dust	uniform

5		Mild steel	Atmosphere	Uniform pitting
6		Brass cartridge	NaCl solution	De alloying, uniform, pitting, crevice in gears
7		HSS	Moist soil	uniform
8		Mild steel	Tap water	uniform
9		Mild steel	Atmosphere	Uniform, pitting
10		Mild steel	Natural water	Uniform, pitting
11	 	Mild steel	kerosene	pitting
12		Cast iron	kerosene	Pitting, crevice, uniform
13		Cast iron	Natural water	Uniform
14		Aluminum alloy	NaCl solution	Mainly Pitting, uniform
15		Al alloy (Ni plated)	NaCl solution	Intergranular, crevice
16		Steel pipe(galvanized)	NaCl	Uniform,galvanic Pitting

17		Steel bolt(Cr plated)	NaCl	Uniform, crevice Intrgranular
18		Galvanized steelcomponent	NaCl	Pitting
19	 	Al alloy(Cr plated)	Tap water	Pitting, crevice is also possible De alloying
20	 	HSS	Tap water	Uniform
21		Low carbon steel	Sulfuric acid	Pitting, uniform, erosion, intergranular
22		Low carbon steel	Mild-Nitric acid	Pitting& uniform
23		Low carbon steel	Concentrated Nitric acid	Pitting, uniform, intergranular & erosion

Cartridge brass that was exposed to sodium chloride solution environment was attacked uniformly and de-alloying was highly demonstrated; on nickel plated aluminum alloy exposed to sodium chloride solution an intergranular corrosion form was observed. Metals including cast iron and steel exposed to kerosene were attacked mainly by pitting. Galvanized steel pipe exposed to sodium chloride solution was shown corroded by pitting and uniform type, which indicates that water pipes of underground type have been corroded easily due to chloride effects in water.

Quantitative analysis of corrosion rate and weight loss after corrosion was carried out using the results obtained from the experiment.

Usually 3 main methods are used to analyze corrosion rate of the material exposed to particular environment, which include: thickness reduction of the material per unit time; weight loss per unit area and unit time; and corrosion current density.

Thickness reduction per unit time is the measure of most practical significance and interest. In the metric system this measure is usually expressed in mm/year. Here the test specimens were weighed before and after the exposure to the corrosion medium. On this basis calculation of thickness reduction as weight loss per unit area/density was conducted using equation (1).The data generated for corrosion test is given in table2.

Table 2 experimental analysis results

Exp. No.	**Material (specimen)**	**Surface Area(cm^2)**	**Volume (cm^3)**	**Weight before exposure(g)**	**Density (g/cm^3)**	**Environment**	**Exposure Time(hr)**	**Weight after exposure(g)**	**Change in weight(g)**	**Corrosion rate(MDD)**	**Form of corrosion**
1	Cast iron	-	-	389.56	6.8-7.8	Oil +dust	360	389.41	0.15	-	Uniform pitting
2	Mild steel sheet	50.44	24.36	190.60	7.85	NaCl solution	360	190.36	0.25	4.21	Uniform pitting
3	Mild steel sheet	154.82	7.566	50.60	7.85	Moist soil	360	50.37	0.23	1.26	uniform
4	Mild steel sheet	159.58	7.8	52.34	7.85	Oil +dust	360	52.14	0.20	1.06	uniform
5	Mild steel	213.66	30.24	243.21	7.85	Atmosphere	360	243.18	0.03	0.12	Uniform pitting
6	Brass cartridge	-	-	214.64	8.4-8.7	NaCl solution	360	214.46	0.18	-	Dealloying
7	HSS	23.76	2.88	26.33	7.48-8.0	Moist soil	360	26.31	0.02	0.72	uniform
8	Mild steel	43.47	13.68	105.01	7.85	Tap water	360	104.65	0.36	7.03	uniform
9	Mild steel	143.43	46.07	322.19	7.85	Atmosphere	360	322.02	0.17	1.00	uniform
10	Mild steel	50.44	24.36	190.36	7.85	Natural water	360	190.07	0.29	4.88	uniform

11	Mild steel	43.43	13.68	104.65	7.85	kerosene	360	104.59	0.06	1.17	pitting
12	Cast iron	12.80	7.29	17.72	6.80-7.80	kerosene	360	17.67	0.05	3.57	pitting
13	Cast iron	12.80	7.29	18.17	6.80-7.80	Natural water	360	18.1	0.07	4.99	uniform
14	Aluminum alloy	28.72	4.64	12.44	2.56-2.80	NaCl solution	360	12.41	0.03	2.60	pitting
15	Al alloy (Ni plated)	-	-	45.39	2.56-2.80	NaCl solution	360	45.37	0.02	-	intergranular
16	Steel pipe(galvanized)	-	-	72.14	7.85	NaCl	360	71.99	0.15	-	Uniform Pitting
17	Steel bolt(Cr plated)	-	--	10.08	7.85	NaCl	360	10.04	0.04	-	Uniform Intergranular
18		-	-	33.45	-	NaCl	360	33.37	0.08	-	pitting
19	Al alloy(Cr plated)	-	-	114.25	2.56-2.80	Tap water	360	113.68	0.58		Pitting Dealloying
20	HSS	23.76	-	26.31	7.48-8.0	Tap water	360	26.22	0.09	3.26	Uniform
21	Low carbon steel	14.29	13.40	104.47	7.85	Sulfuric acid	24	98.03	6.44	5740.95	Pitting, uniform
22	Low carbon steel	8.97	2.73	189.94	7.85	Nitric acid	24	-	-	-	Pitting, uniform, erosion, intergranular
23	Low carbon steel	14.41	13.49	104.8	7.85	Nitric acid	0.25	97.04	7.76	658566.01	Pitting, uniform, erosion, intergranular

From the table it is possible to conclude that the corrosion rate and weight loss of the material have direct relationship in which, when the rate of corrosion increases the weight loss of the material increases. Based on the table above environments, which corrode the materials more comparing to the others was identified. Accordingly, the least corrodible material is HSS that both the corrosion rate and weight lose are less even though it was exposed to moist soil. Weight loss of aluminum is very small but its corrosion rate is high when it was exposed to sodium chloride media. It is because the nature of aluminum is that when exposed to any corrosive environment it oxidizes easily and protects itself acting as an insulator. It may develop passivity to the electro chemical reaction. However a little corrosion is observed due to the reaction of aluminum with chlorides which form a new salt that may lead to crevice and pitting corrosions as chloride is the main cause of crevice corrosion and pitting and mechanism of crevice and pitting corrosion is almost the same. The chemical reaction of aluminum and NaCl solution may take the form:

$$Al + 3NaCl \rightarrow AlCl_3\downarrow + 3Na \quad (3)$$

Metal ion reduction $Al \rightarrow Al^{3+} + 3e$ (4)

Considering that the Na and Cl are not included in the corrosion process and NaCl is a neutral solution the cathodic reaction will get the form:

$$O_2 + 2H_2O + 4e \rightarrow 4OH \quad (5)$$

In this case metal deposition increases towards the crevices due to the presence of chloride ion.
For mild steel that was exposed to tap water, both the corrosion rate and weight lose is very high. It is known that mild steel contains iron and carbon. Neglecting the trace elements present in the steel, which have insignificant role on corrosion formation the reaction of water with iron, will get the already theoretically and practically known form as follows:

$$Fe + H_2O \rightarrow FeO\downarrow + H_2 \quad (6)$$

The anodic reaction is

$$Fe \rightarrow Fe^{2+} + 2e \quad (7)$$

As water is neutral solution, the cathodic reaction will be

$$O_2 + 2H_2O + 4e \rightarrow 4OH^- \quad (8)$$

Ferrous hydroxide precipitates in from solution. Since the compound is unstable type in oxygenated solutions since it oxidized to ferritic salt, the reaction will be:

$$2Fe(OH)_2 + H_2O + 1/2O_2 \rightarrow 2Fe(OH)_3 \quad (9)$$

Mild steel with very small cross sectional area, which was exposed to sodium chloride solution, has relatively high corrosion rate and weight loss, which tells us that sodium chloride is a very strong corrosive environment to this steel. The corrosion reaction shows the form :

$$Fe + 2NaCl \rightarrow FeCl_2\downarrow + 2NaOH \quad (10)$$

The anodic reaction in this case is $Fe \rightarrow Fe^{2+} + 2e$
Cast iron exposed to natural water, oil and dust as well as kerosene environments show different corrosion rates, in which the one exposed to oil and dust mixture environment was corroded highly.

Aluminum alloys of different composition exposed to similar environments also show different rate of corrosion, the nickel alloyed aluminum showed better resistant to NaCl solution than the others, which confirms that different alloying elements have different corrosion resistivity for the same environment.
Based on the experimental results from table 2 graphic representation of corrosion rate vs. environment and weight loss vs. environment for, which mild steel was exposed is plotted in figure 1. As the figures show the rate of corrosion and weight lose increases with increasing of

concentration of environment. The higher environmental effect was seen on mild steel samples exposed to nitric acids and sulfuric acids.

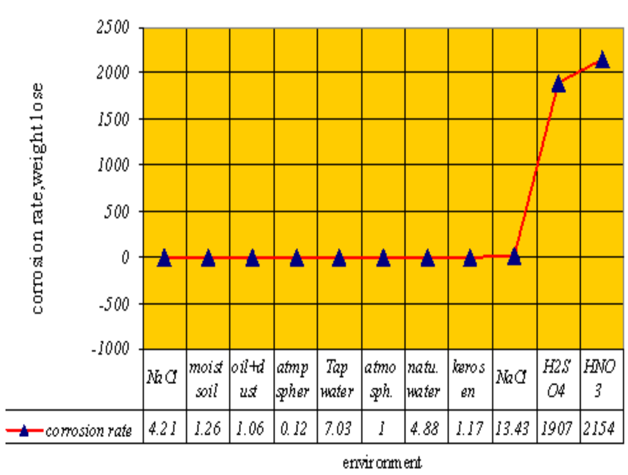


Figure1 Materials exposed to different corrosive media vs. corrosion rate

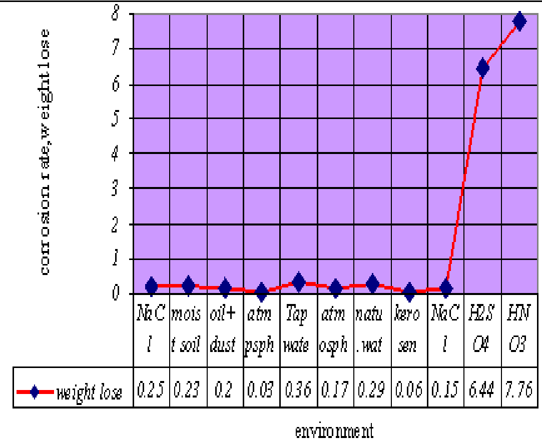


Figure 2 Materials exposed to different corrosive media vs. weight lose

It implies that the acidic environments both sulfuric and nitric acids are dangerous environments for mild steel. In this regard from the experiment uniform and pitting corrosion were developed in most environments .Crevice corrosion follows pitting corrosion. Though all environments cause corrosion, acidic environments are highly affecting the metals. This is because of the presence of H^+ which is indicator of strong acidic behavior and the mentioned acids are strong by their nature .The products after dissociation is H+ and $HSO_4^-H^+$and NO_3^- which tells us the dissociation of metal goes to even liquid slurry.

From equations it is clear that metal is eroded by the acid that is why the mild steel pieces have been disintegrated highly than the others. Thus care must be taken towards these aggressive environments not to contact with these specific metals.

4. Conclusion

Based on the experiment results given it is possible to conclude that corrosive environments effect on materials is high and dangerous that it could cause plant shut down, and priority of protection of mild construction steels from acidic environments of concentrated type is essential part of corrosion protection method. Thus further study on the effect of each environment on individual materials in this regard is a critical issue, especially mixture environments like oil with dust, the study will help to establish and implement the proper corrosion protection method in metal industries. It should be noted that all specimens exposed to any environment were affected by uniform corrosion which is obvious from literature and experience.

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