International Journal of Applied Engineering Research ISSN 0973-4562 Volume 13, Number 19 (2018) pp. 14188-14195

Theoretical Approach and Experimental Studies on the Reliability–Corrosion

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Abstract

This paper presented the estimation of system reliability-corrosion using two parameter Weibull distributions with new corrosion problem in connection of the modern concepts, we present a new method to study the corrosion problem of development of metals and alloys. For this, we first consider this type of corrosion as a phenomenon of damage. Quantitatively, this phenomenon we associate with a time dependent parameter D.By establishing a relationship between the corrosion factor $D(t)$ and reliability $R(t)$, which is the probability of survival of the material in question. We can extract important information. Indeed, this relationship allows us to determine the critical moment which corresponds to the acceleration of the damage (or corrosion). In fact such a relationship is crucial from the point of view of preventive maintenance. Then our theoretical predictions are compared with experimental results (Diesel Engine) [1-3].

Keywords: Reliability-Corrosion, Damage, Weibull distributions, Diesel Engine.

INTRODUTION

Corrosion is the deterioration or destruction of metals and alloys in the presence of an environment by chemical or electrochemical means. In simple terminology, corrosion processes involve reaction of metals with environmental species. Also it can be viewed as a universal phenomenon omnipresent and omnipotent. It is there everywhere, air water soil and in every environment. We encounter, that affects all types of materials including metals and alloys. In fact, a metal stored in a vacuum or with a perfectly insulated surface remains stable indefinitely. However, if the insulation is imperfect, the metal surface in contact with the environment may. In some cases, undergo significant changes. Under these conditions, the metal is less stable and becomes susceptible to corrosion that occurs in many different aspects.

Corrosion is defined as the physical-chemical interaction between a metal and its environment causing changes in the properties of metal and often a functional deterioration of the metal itself, the environment or the system composed of these two factors. Only rare noble metals like gold or platinum are found naturally in metallic form. In fact, most of the metals are present as oxides sulphates, sulphides, carbonates or chlorides that are the main types of ores. Reduced to the metallic state, they tend. in some circles to return to the oxidized form which is thermodynamically more stable. This corrosion phenomenon, which is essentially chemical causing heavy economic losses and a significant loss in terms of raw materials and energy.

We note, moreover, that the laws of deterioration due to corrosion are far from being well known contrary to the laws governing wear. This is mainly due to the abundance of the parameters that cause the phenomenon. Only the experimental method seems well suited to monitor the corrosion rate.

The materials may undergo several types of corrosion, we can find the dry corrosion [4.5] and corrosion in aqueous media [6]. The first is mainly due to the attack of a metal by a gas, the second takes place in environments where the relative humidity exceeds 60% or outright in an aqueous solution. This classification is simplistic however because there are cases in liquid medium without the aqueous corrosion. Another form is frequently encountered, it is the electric corrosion in which two metal surfaces are subject to a sufficient potential difference to create an electric arc thus causing a kind of abrasion. This phenomenon comes from a setting to the ineffective ground induced currents on electrical machines or electrostatic friction loads (belts. textiles. etc.). There is also a special case of corrosion, it is caused by living organisms (biochemical corrosion). This is the case for example bacterial attack [7], indeed cutting oils and industrial water often contains iron bacteria that divide every 20 minutes. Thus. A bacterium gives rise to a billion bacteria every 12 hours. Fretting corrosion is the fifth mode which occurs when two metal contact parts are subjected to vibration. In this case there is formed a reddish highly abrasive dust Fe_2O_3. Finally cavitation is also a mode of corrosion which occurs on the parts in contact with a turbulence in the liquid. It should be noted that each of these families corrosion admits symptoms and specific solutions. These symptoms thus alert the technician who must appeal to specialists to recommend corrective action (or preventive) needed. Preventive maintenance [8,9] is the only way then to intervene in time to prevent a disaster that could be caused by corrosion.

In previous work [10,11], we had been interested in the study of mechanical damage [12] Composite materials [13,14] (laminated fiber glass-epoxy) that had been studied in terms of reliability using a statistical approach [15-19]. This reliability is the probability of survival of the material at the time

concerned. This work on mechanical damage inspire us to consider the idea that corrosion is a wear and degradation phenomenon, this invites us to define a parameter of damage (corrosion factor). D, which is a function of all the parameters of the problem and is likely to follow the evolution of this degradation. In addition. We offer an adjusted law of reliability $R\ (t)$, which is the Weibull distribution [15,16]. In fact, the reliability and the damage parameter vary over time in opposite directions. Such approach is very important because it allows to predict the time $t_{c,}$ which announces the critical stage of corrosion. Therefore, this allows timely intervention (preventive maintenance) appropriate and effective.

In what follows, we focus only on the wet corrosion. This type of corrosion is characterized by a negative result, the point of view of security of the material and may lead to penetration in the thickness of the latter. For quantitative results, we consider a general law of corrosion but the discussion can be extended to other i.e. linear laws parabolic cubic and logarithmic [20]. Finally, our results are compared with those reported in recent experiments [1-3].

This work is organized as follows. In Section 2. We recall the form of the general law of corrosion. The approach to reliability is the purpose of Section 3. A comparison with experiment is discussed in Section 4. Finally. Some concluding remarks are presented in the last section.

THEORETICAL FORMULATIONS

1. General Law of corrosion

We first note that the corrosion is caused by several types of effects: dissolution of metals in water appearance of electrochemical cells existence of concentration gradients, differential aeration or pitting.

As in the dry corrosion, wet corrosion reactions are possible only if the free energy of the reaction products is lower than the free energy of the reactants. This is the case, however reaction of almost all metals in the presence of water and oxygen to give rise to metal hydroxides according to the chemical reaction:

$M + H_2O \rightarrow M(OH)_2$.

The wet corrosion rate can often be very high compared to that of the dry corrosion at the same temperature. There are two main reasons for this:

- First the water molecule dipole stabilizes the free metal ions (dissociated) in solution;
- Second. The metal structure and the water in contact can conduct an electrical current. On the other hand the etching process depends on the availability of oxygen (Fig.1).

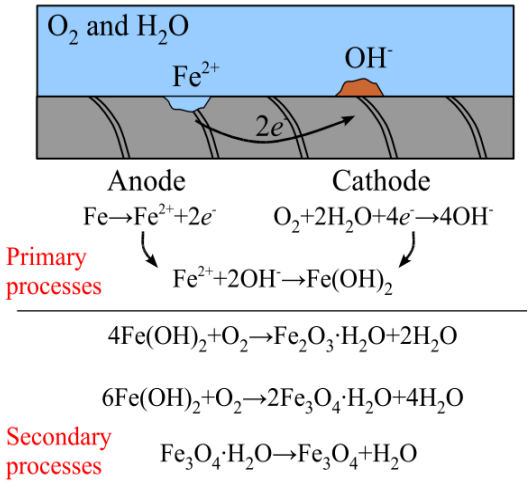

Figure 1: Electrochemical corrosion mechanism of Iron [21]

Corrosion products in particular hydroxides may cause a reduction of the oxygen because the latter diffuses through these deposits and form a more or less continuously on the metal surface layer Since the metal dissolution rate equals the rate of oxygen reduction a limited supply and a limited reduction in oxygen levels also reduce the corrosion rate. In this case, it is said that corrosion is under cathodic control. This is a widespread mechanism for limiting corrosion by nature. It is very useful to use the Avramy law [22, 23], which can accurately describe the kinetics of chemical reaction rates giving the fraction of processed material after a certain time and at a given temperature. We can express a part of a reacted material in an oxidation reaction over time.

By an amount f, which may be normalized by the volume of the sample under consideration.

The generally accepted empirical rate equation that most describe the isothermal kinetics of recrystallization requires measurement of the recrystallized volume fraction f and can be can be expressed as [24]:

$$\frac{df}{dt} = \beta(\eta)^{-\beta} t^{\beta-1}(1-f) \qquad (1)$$

Where β is the order of the reaction. And the factor $(1-f)$ may be regarded as an allowance for retardation in reaction rate due to impingement. Assuming η^{-1} and β to be true constants independent of f (and thus of t) for a given temperature, the integration of Eq. (2) yields:

$$\ln\frac{1}{1-f} = \left(\frac{t}{\eta}\right)^{\beta} \qquad (2)$$

which yields a sigmoidal rate curve and can be also expressed as [25–27]:

$$f(t) = 1-\exp\left\{-\left(\frac{t}{\eta}\right)^{\beta}\right\} \qquad (3)$$

Eq. (3) is attributed to Kolmogorov [25], Johnson, Mehl [26] and Avrami [9] is commonly known as *JMAK*. The *JMAK* equation is strictly valid only when the recrystallized grains are distributed randomly and when the grains are growing independently of one another [28]. The order of the reaction n also known as the Avrami or *JMAK* exponent reflects the nucleation rate and/or the growth morphology and k is the pre-exponential factor. A kinetic parameter depending on the annealing temperature nucleation rate and growth rate. In general n takes the value of $1 \le \beta \le 2$ for one-dimensional growth $2 \le \beta \le 3$ for two dimensional growth and $3 \le \beta \le 4$ for three-dimensional growth [24]. For no change in mechanism β is insensitive to temperature. Whereas k is the temperature-dependent constant expressed as [27]:

$$\eta = \eta_0 \exp\left(\frac{Q}{RT}\right) \tag{4}$$

Where η_0 is a constant, Q the activation energy, R the gas constant ($R = 8.314472\ J\ mol^{-1}K^{-1}$) and T is the absolute annealing temperature.

2. Corrosion Factor

Corrosion on the other hand could be defined simply as a process by which a metals chemical structure is changed resulting in gradual deterioration by being slowly 'eaten' away in a chemical oxidation-reduction reaction. The interaction of fatigue and corrosion is called corrosion fatigue, Corrosion is stopped at the end of the reaction of the entire volume of the material. Since the amount $f(t)$ mentioned above is likely to describe the evolution of damage caused by the corrosion phenomenon. We can define a corrosion factor. $D(t)$ by

$$D(t) = 1 - \exp\left\{-\left(\frac{t}{\eta}\right)^{\beta}\right\} \tag{5}$$

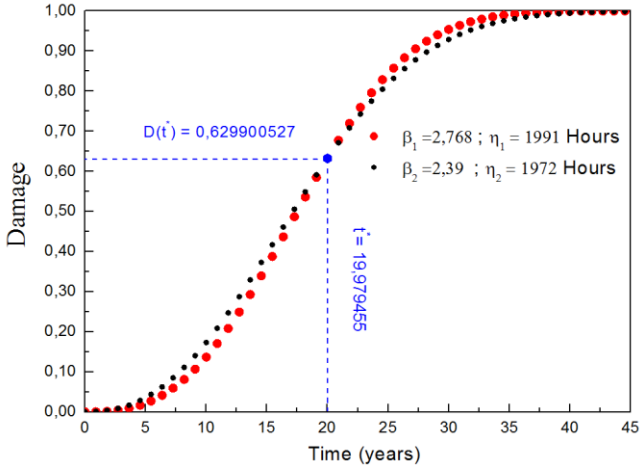

Figure 2: The corrosion factor $D(t)$ as a function of time.

First, the corrosion factor $D(t)$ remains within the interval [0.1]. For a virgin material $D = 0$ and $D = 1$, when it is completely corroded.

Second, the corrosion factor is a monotonically increasing function of time from $t = 0$ to $t = 1$.

The equation (4) may be written

$$\ln\left[\ln\left(\frac{1}{1-D(t)}\right)\right] = \beta \ln t - \beta \ln \eta \,. \tag{6}$$

The equation (5) can now be rewritten in linear form as follows

$$y(t) = \beta x(t) - \beta \ln(\eta) \tag{7}$$

With

$$y(t) = \ln\left[\ln\left(\frac{1}{1-D(t)}\right)\right] \quad \text{and} \quad x(t) = \ln(t) \tag{8}$$

This is now a linear equation. With a slope of β and an intercept of $\beta \ln(\eta)$. Now the x- and y-axes of the Weibull probability plotting paper can be constructed. The x-axis is simply logarithmic since $x(t) = \ln(t)$. The y-axis is slightly more complicated since it must represent

$$y(t) = \ln\left[\ln\left(\frac{1}{1-D(t)}\right)\right] \tag{9}$$

The following paragraph is devoted to the concept of reliability.

3. Reliability measures

Reliability, we mean the probability of survival of the material at the time concerned. This statistical value is of paramount importance because it can track the degradation of a material over time. The reliability approach is proving to be a valuable tool for preventive maintenance.

The damage meanwhile is a factor related to the deterioration of the material, while reliability is statistical. In fact, these two entities are inversely related to each other. Indeed, a blank material has a reliability equal 1 and 0 factor damage. But a completely faulty material corresponds to zero reliability and a damage factor of 1.

The law reliability appears to be the most suitable for this kind of degradation is the Weibull [15,17], which is based on the fact that the failure rate evolves as any power of time. This constraint is perfect for us since as and that the oxide layer develops on metal it is less able to properly perform its functions and so the probability of failure increases. In addition this distribution includes others such as the normal distribution and the exponential distribution. The reliability associated with the Weibull distribution is given by

$$R(t) = \exp\left\{-\left(\frac{t}{\eta}\right)^{\beta}\right\}. \tag{10}$$

Where η and β are parameters. The scale parameter η reflects the size of the units in which the random variable t is measured. The shape parameter β causes the shape of the distribution to vary. By changing the value of β we can generate widely varying set of curves to model real lifetime failure distributions.

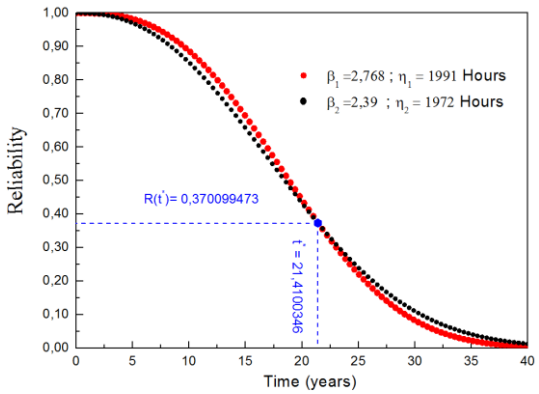

Figure 3: The Reliability (survival) function $R(t)$ as a function of time.

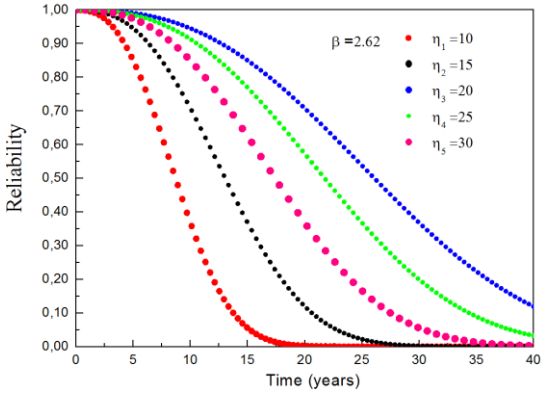

Figure 4: The Reliability (survival) function $R(t)$ as a function of time for different values of η with $\beta = 2.62$

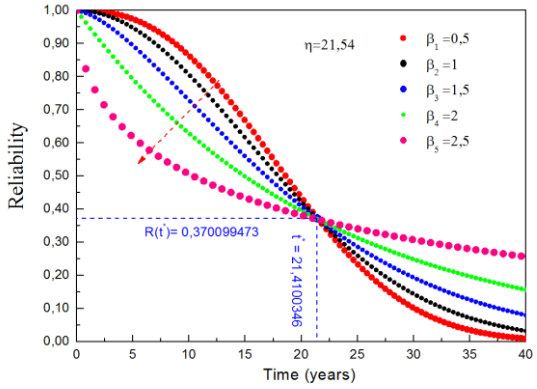

Figure 5: The Reliability (survival) function $R(t)$ as a function of time for different values of β with $\eta = 21.54$

The Weibull Failure Rate Function (FRF) is defined as the number of failures per unit time that can be expected to occur for the product. It is given as.

$$\lambda^{FRF}(t) = \frac{\beta}{\eta} \times \left(\frac{t}{\eta}\right)^{\beta-1} \tag{11}$$

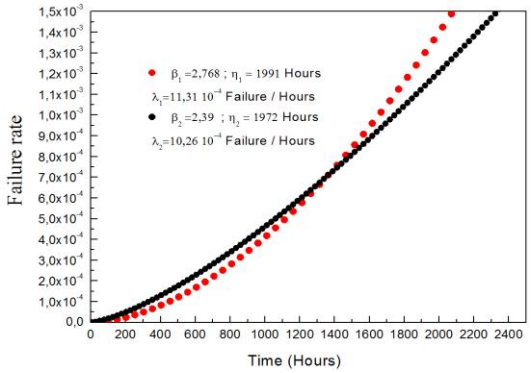

Figure 6: The Weibull Failure Rate Function (FRF) as a function of time with $\beta_1 = 2.768$ and $\eta_1 = 1991$ Hours (red scatter).

$\beta_2 = 2.39$ and $\eta_2 = 1972$ Hours (black scatter).

The two-parameter Weibull Probability Density Function (PDF) $F^{PDF}(t)$ is given as

$$F^{PDF}(t) = \lambda^{FRF}(t) \times R(t) = \frac{\beta}{\eta} \times \left(\frac{t}{\eta}\right)^{\beta-1} \times \exp\left(\frac{t}{\eta}\right)^{\beta} \tag{12}$$

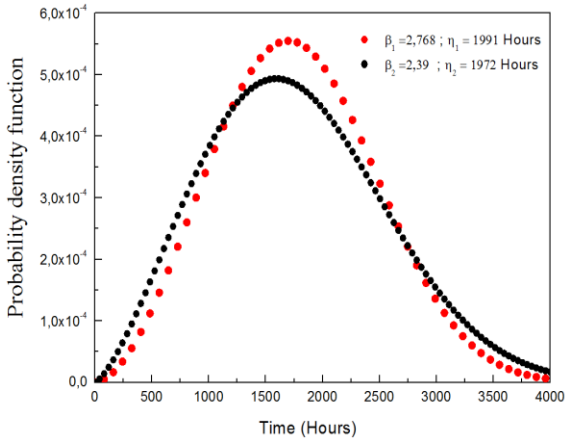

Figure 7: The Weibull Probability Density Function $F^{PDF}(t)$ as a function of time. $\beta_1 = 2.768$ and $\eta_1 = 1991$ Hours (red scatter).

$\beta_2 = 2.39$ and $\eta_2 = 1972$ Hours (black scatter).

The mean life or mean time of failure (MTTF) or Mean Time between Failure (MTBF) is defined as the average time of failure-free operation up to a failure event calculated from a homogeneous lot of equipment's under operation. The MTTF or MTBF of the Weibull PDF used for 2 and 3- parameter Weibull distribution is given as:

✓ ***For 2- parameter Weibull distribution***

$$MTBF(\eta,\beta)=\eta\times\Gamma\left(\frac{1}{\beta}+1\right)=\frac{\eta}{\beta}\times\Gamma\left(\frac{1}{\beta}\right) \quad (13)$$

$$\Gamma(z)=\int_0^{\infty}\mu^{z-1}\exp(-\mu)d\mu \quad (14)$$

Where, the gamma function is previously defined (see Appendix A).

The variance is given by

$$\sigma^2(\eta,\beta)=\eta^2\times\left[\Gamma\left(\frac{2}{\beta}+1\right)-\left(\Gamma\left(\frac{1}{\beta}+1\right)\right)^2\right] \quad (15)$$

Numerical application example see Appendix A

β	$\eta(Hours)$	$MTBF(Hours)$	t_m	σ
1/3	16000	96000	5328.4	418454.29

✓ ***For 3- parameter Weibull distribution***

$$E^{MTBF}(T)=\gamma+\eta\times\Gamma\left(\frac{1}{\beta}+1\right)=\frac{\eta}{\beta}\times\Gamma\left(\frac{1}{\beta}\right) \quad (16)$$

The variance is given by

$$\sigma^2(\eta,\beta)=\eta^2\times\left[\Gamma\left(\frac{2}{\beta}+1\right)-\left(\Gamma\left(\frac{1}{\beta}+1\right)\right)^2\right] \quad (17)$$

At this stage, we are able to connect to the corrosion reliability factor. A trivial comparison of equalities (4) and (7) leads to the desired relationship

$$D(t)+R(t)=1. \quad (18)$$

This basic relationship deserves some comment:

First, the curve describing the evolution of the reliability depending on the corrosion factor is naturally decreasing from $D=0$ to $D=1$.

Second, such a relationship allows us to go directly to the reliability at each stage of corrosion. Moreover. Beyond a value of D which is less than 0.5, the reliability starts to drop quickly. This is consistent with what is observed in Fig.1, namely that beyond $D=0.5$ the material is sufficiently corroded.

Finally, the critical time t_c at which the corrosion process becomes accelerated. Quantitatively, this time is the abscissa the intersection of the curves representing the change with time of the reliability and the corrosion factor.

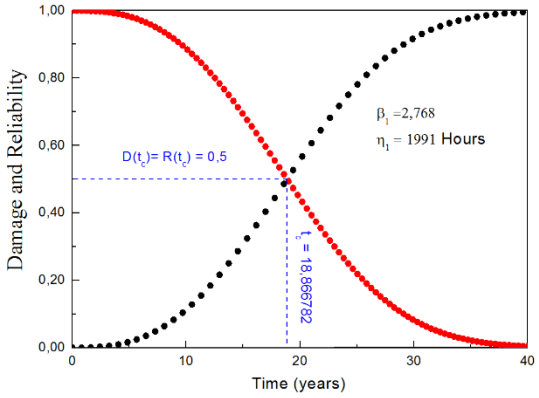

Figure 8: The Reliability (survival) function and The Damage factors as a function of time with $\beta_1=2.768$ and $\eta_1=1991$ Hours.

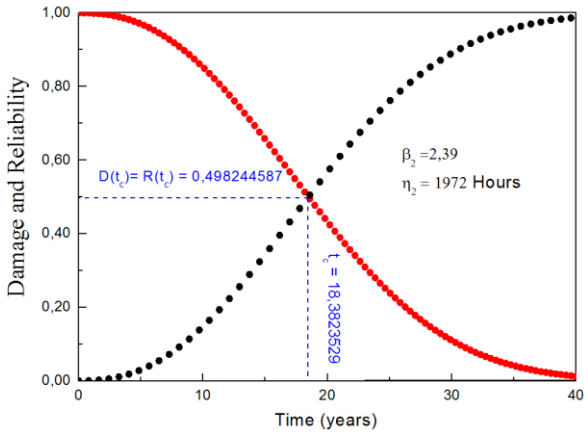

Figure 9: The Reliability (survival) function and The Damage factors as a function of time with $\beta_2=2.39$ and $\eta_2=1972$ Hours.

To determine the failure density function f (t) is equals the relation between the number of failures in the time interval and the total number of systems. failure rate function λ (t) will equal the relation between the number of failures in the time interval and the number of systems which did not fail at the end of the time interval and The reliability function R (t) will equal the relation between the number of systems which did not fail at the end of the time interval and the total number of systems [1-3].

Table 1. Calculated values of empirical function

β	η	$D(t)$	$R(t)$	$\lambda(t)10^{-4}$	E^{MTBF}	$F^{PDF}10^{-4}$	σ
2.768	1991	0.1157	0.8843	22.71	20.082	1772.1	15.514
2.390	1972	0.1371	0.8644	18.06	15.611	1748.0	17.536

In the next paragraph, we will compare theoretical predictions described above to the experimental results [1-3].

COMPARISON WITH EXPERIENCE

It is well known that wet corrosion has generated much interest in the past in particular from an experimental point of view. In this work, we focus on some experience [1-3]. Which was held was held at company service station for thirty same Make & Model diesel engines for compressor application .The failure of engine are consider only cooling system. First phase data collecting from the maintenance record of service station logbook period of two year is taken. Then data is sorted & classified based on engine number failure hour & failure subsystem. The cooling system failure data shown in Table 2, we use the experimental results to extract the damage and the reliability each Engine N for different β and η.

Table 2. Data on failure cooling system of Diesel Engine.

		$\beta_1 = 2.768$ $\eta_1 = 1991$		$\beta_2 = 2.39$ $\eta_2 = 1972$	
Engine N	TF	$D_1(t)$	$R_1(t)$	$D_2(t)$	$R_2(t)$
1	127	0.25312	0.74688	0.2976	0.7023
2	720	0.05812	0.94188	0.0860	0.9139
3	113	0.19027	0.80973	0.2343	0.7656
4	185	0.55997	0.44003	0.5780	0.4219
5	168	0.46856	0.53144	0.4977	0.5022
6	257	0.86828	0.13172	0.8479	0.1520
7	244	0.82722	0.17278	0.8105	0.1894
8	254	0.86155	0.13845	0.8417	0.1583
9	110	0.17595	0.82405	0.2194	0.7805
10	211	0.69429	0.30571	0.6941	0.3058
11	187	0.5718	0.4282	0.5883	0.4116
12	163	0.43882	0.56118	0.4711	0.5288
13	264	0.8889	0.11110	0.8672	0.1327
14	155	0.39675	0.60325	0.4331	0.5668
15	247	0.83735	0.16265	0.8196	0.1803
16	189	0.58195	0.41805	0.5971	0.4028
17	260	0.87862	0.12138	0.8575	0.1424
18	248	0.84064	0.15936	0.8226	0.1773
19	125	0.24095	0.75905	0.2856	0.7143
20	262	0.88424	0.11576	0.8628	0.1371
21	166	0.45808	0.54192	0.4884	0.5115
22	126	0.24888	0.75112	0.2934	0.7065
23	612	0.03747	0.96253	0.0592	0.9408
24	886	0.10087	0.89913	0.1373	0.8626
25	470	0.01822	0.98178	0.0319	0.9680
26	251	0.85024	0.14976	0.8313	0.1686
27	281	0.92575	$7.424\times10^{-}$	0.9032	0.0967
28	211	0.69192	0.30808	0.6921	0.3078
29	401	0.01178	0.98822	0.0219	0.9780
30	190	0.58833	0.41167	0.6026	0.3973

CONCLUSION

Recall that the primary objective of this paper is the introduction of a statistical tool, based on the important concept of reliability, to track the phenomenon of corrosion of metals and alloys, over time. This reliability represents, in fact, the survival probability of the system. Through its relationship with the corrosion factor, which we have established, we were able to have valuable information about the critical time at which corrosion is accelerated. Knowledge of this characteristic time is crucial to intervene in time to avoid any functional damage.

For conducting explicit calculations, we chose the Avramy law, because the latter is more general to describe the spread of corrosion. As we noted above, this law has been favorably tested by using data from some recent research regarding the reliability of cooling system diesel engine [1-3]**.**

We can say that the model used can be extended to porous materials. In this case, the constants of the material described above strongly depend on the structure of the material, such as pore size distribution, connectivity, but the theoretical method may face other experiences.

APPENDIX A.

➢ The aim of this appendix is to demonstrate formula (8).

$$MTBF(\eta,\beta)=\int_0^\infty R(t)\,dt=\int_0^\infty \exp\left\{-\left(\frac{t}{\eta}\right)^\beta\right\}\,dt$$

Make the substitution

$$\mu=\left(\frac{t}{\eta}\right)^\beta$$

$$\mu^{\frac{1}{\beta}}=\frac{t}{\eta}$$

$$\frac{1}{\eta}dt=\frac{1}{\beta}\mu^{\frac{1}{\beta}-1}$$

Then we arrive at (9a)

$$MTBF(\eta,\beta)=\frac{\eta}{\beta}\int_0^\infty \mu^{\frac{1}{\beta}-1}\,\mathrm{e}^{-\mu}\;dt=\frac{\eta}{\beta}\times\Gamma\left(\frac{1}{\beta}\right)$$

➢ Numerical application example

β	$\eta(Hours)$
1/3	16000

The MTBF is

$$MTBF(\eta,\beta)=\eta\times\Gamma\left(\frac{1}{\beta}+1\right)$$
$$=16\times10^{3}\ \Gamma(4)$$
$$=16\times10^{3}\times3!$$
$$=96\times10^{3}\ \text{Hours}$$

The median life is given by

$$R(t_m)=\frac{1}{2}$$
$$\exp\left(\frac{t_m}{\eta}\right)^{\beta}=\frac{1}{2}$$

Given values of β . η give

$$t_m=\eta(\ln 2)^{1/\beta}=16000(\ln 2)^{3}=5328.4$$

The median life is a better measure than the mean life since the Weibull probability density function. is highly skewed.

The variance is given by

$$\sigma^2(\eta,\beta)=\eta^2\times\left[\Gamma\left(\frac{2}{\beta}+1\right)-\left(\Gamma\left(\frac{1}{\beta}+1\right)\right)^2\right]$$
$$\sigma^2=(16000)^2\times\left[\Gamma(7)-(\Gamma(4))^2\right]$$
$$\sigma^2=(16000)^2\times\left[6!-(3!)^2\right]$$
$$\sigma = 418454.29$$

ACKNOWLEDGMENTS

The authors are thankful to Prof. H. Ridouane for his valuable remarks and discussion, which made it possible to reevaluate the work from another view- point.

AUTHOR CONTRIBUTIONS

Both authors contributed equally to the development of this paper.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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