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Estimation of fatigue-corrosion damage and life under variable loading based on modified corrosion fatigue model (MCFM)

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Abstract

Fatigue damage and life results from the conjoint actions of cyclically applied stress and external environment (chemical) are studied for aluminum (3003-H18) alloy to explore load-environment interaction in fatigue which is essential to the formulate rational life prediction of component and structures. In this study, a modified corrosion-fatigue model (MCFM) based on the S-N curve and taking into account the effect of load history and corrosion effect was introduced. The obtained results from this model are in good agreement with the experimental results and show a 2.492 safety factor while Palmgren-Miner (PM) rule gave 1.372 factor of safety. The corrosion environment reduces the fatigue endurance limit by 5.06% compared to dry fatigue.

Key words: Modified corrosion fatigue damage model (MCFM), corrosion-fatigue life predictions, aluminum alloy, Miner rule.

الخلاصة

تم دراسة تداخل نتائج ضرر وعمر الكلال تحت الاجهادات الدورية المسلطة والمحيط التأكلي الخارجي لسبيكة الالمنيوم (3003-H18) لمعرفة تداخل الحمل مع المحيط التاكلي والذي هو اساسي لتخمين عمر الكلال. في هذه الدراسة تم اقتراح نموذج متطور لتداخل الكلال مع المحيط التاكلي لتقييم الضرر المتراكم معتمدا على منحني S-N ويأخذ بنظر الاعتبار تأثير تتابع الاجهادات وتأثير المحيط التاكلي . النتائج المستحصلة من الانموذج المقترح كانت لها تطابق جميع النتائج العملية حيث

اعطت عامل امان 2.492 بينما نظرية (PM) اعطت عامل امان 1.37 مقارنة مع النتائج العملية وان المحيط التاكلي يقلل من حد الكلال بنسبة 5.06% نسبة الى الكلال الجاف.

الكلمات المرشدة : انموذج ضرر الكلال الكيمياوي , تخمينات عمر الكلال الكيمياوي ، سبيكة الالمنيوم ، نظرية ماينر

Introduction and literature review

In many engineering applications, metallic materials are used in structures, components, and machinery that are subjected to cyclic loadings and exposed to marine environments often results in a significant reduction in fatigue performance compared with that obtained under cyclic loading in inert environments. Fatigue damage occurring under the conjoint action of cyclic loading and aggressive environment is generally referred to as corrosion fatigue [1]. At the present there is no reliable solution for the fatigue-corrosion of metals [2]. The fatigue behavior of 2024-T4 high strength aluminum alloy in laboratory air and 3.5% NaCl solution was studied using rotary bending technique. The results obtained from S-N curves, showed that the fatigue strength of the above alloy in 3.5%NaCl solution is 2-3 times less than that in dry air [3]. The fatigue behavior of aluminum alloy 5454-H32 was studied under laboratory air and 3% NaCl solution environmental using smooth cylindrical and notched plate specimen. The presence of 3% NaCl solution during fatigue cycling severely reduces the fatigue life of aluminum alloy 5454-H32. The deleterious effect was pronounced in both types of specimens (about 70% reduction in fatigue strength) is observed in the long life (low stress) regions. [4]. The corrosion-fatigue behavior of 7075-T651 aluminum alloy subjected to periodic overloads was examined. This aluminum alloy is typically used in aerospace structural components such as the wing spars of aircraft. The specimens were fatigue tested while they were fully immersed in an aerated and recirculated 3.5 wt% NaCl simulated seawater solution. A damage analysis showed that the presence of the corrosive environment accelerated the damage accumulation rate to a greater extent than that observed in air, particularly at low stress ranges [5]. The effect of seawater corrosion on the fatigue resistance property of 6063 aluminum alloy was studied. The 6063 aluminum alloy that was used for the study soaked in seawater for different intervals of time between 2 and 30 weeks. Generally at constant load, the results indicated that the number of cycles to failure decreased with increasing the soaking time in seawater and the immersion time in seawater of the specimen also affects the fatigue resistance property of the material and cannot be ignored[6].A Corrosion fatigue behavior of the AZ91C Mg-alloy was determined through the use of plane-bending corrosion fatigue machine with stress ratio R=0.5 and under constant frequency of 10 Hz. Preliminary results show that in 3.5% NaCl fatigue life (N_f) decreases with an increase of pH from 1 to 6 and was constant at pH=7, 9 also it is noted that the fatigue life of magnesium alloy in such corrosive solutions as, for example, NaCl, is always less than that in air[7].

Most of previous work used Miner rule or modified Miner rule to estimate the fatigue life under corrosion condition while in this study a new model based on the loading sequences, mechanical properties and test conditions was presented.

Experimental work

1- Material

The aluminum alloy is widely used in the aging aircraft due to its high strength to density ratio. However this Aluminum (3003-H18) alloy is susceptible to corrosion damage. The chemical composition of the above alloy is presented in table (1) while the experimental mechanical properties with the standard values are listed in table (2).

Table (1): Chemical composition of Aluminum (3003-H18) alloy in wt%

Elements	Si	Fe	Cu	Mn	Zn	Rem.
Standard Values (ASM) Wt%	0.60	0.70	0.05-0.20	1.0-1.5	0.10	Al
experimental	0.167	0.483	0.0601	0.645	0.310	Al

Table (2): Mechanical properties of Aluminum (3003-H18) alloy

Property	Tensile strength σ_u (Mpa)	Yield Strength σ_y (Mpa)	Elongation%	Modulus of elasticity (Gpa)
Standard (ASM)	200	186	4	69
Experimental	205	196	5	72

2-Fatigue Test Specimens Preparation:

The specimens were prepared according to ASTMD3479/D3479M–96, standard test method for fatigue of aluminum(3003-H18) alloy .Fatigue specimens were cut in suitable dimensions to satisfy the machine test section that suited for flat plate specimens. Figure (1) shows the fatigue test specimens and its configuration.

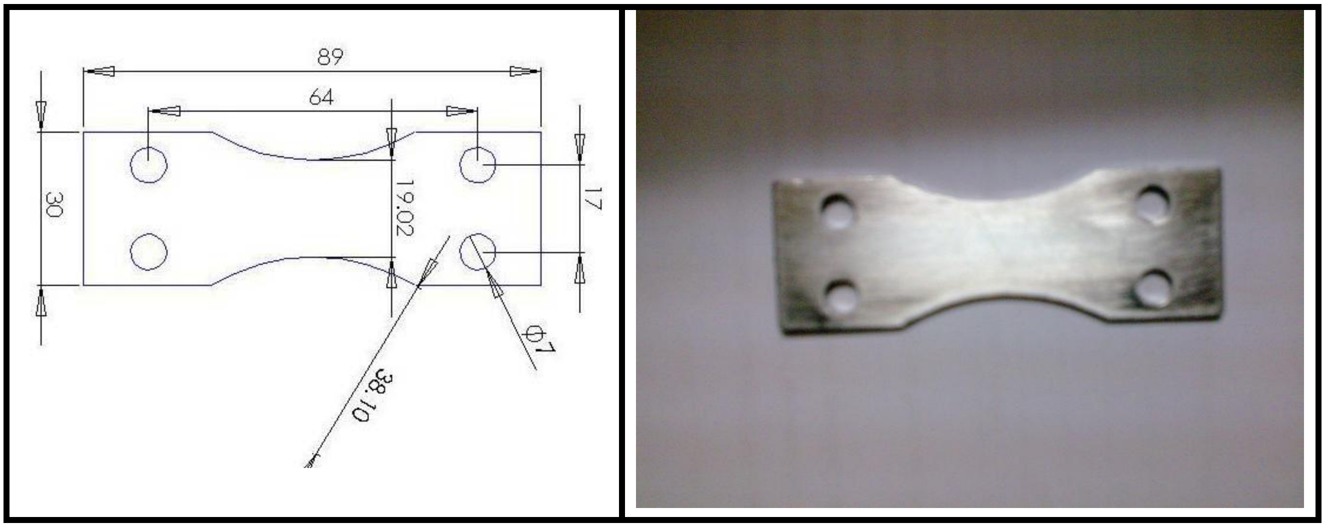

Figure (1): Fatigue Specimen (all dimension in mm)

3-Fatigue Tests Procedure:

All fatigue tests were carried out in the laboratories of electromechanical engineering department, University of Technology using AVERY fatigue testing machine Type-7305.The experiments were conducted at room temperature and at stress ratios R=-1. Figure (2) shows the fatigue test rig

Figure (2): AVERY Fatigue Testing Machine Type 7305

4-Test environment:

Corrosion fatigue tests were performed in a 3.5% wt NaCl aqueous solution. The NaCl solution used in this investigation was a 3.5% mass mixture of sodium chloride (NaCl) salt and distilled water corresponding approximately to the composition of salt water. The aerated solution was circulated from and to a reservoir via corrosion cell fitted on the specimen at room temperature. Each reservoir contained a liter of simulated seawater solution .The corrosion cell developed to conduct the aggressive environment tests is shown in figure (3).While the failure was defined as the specimen is broken into two parts

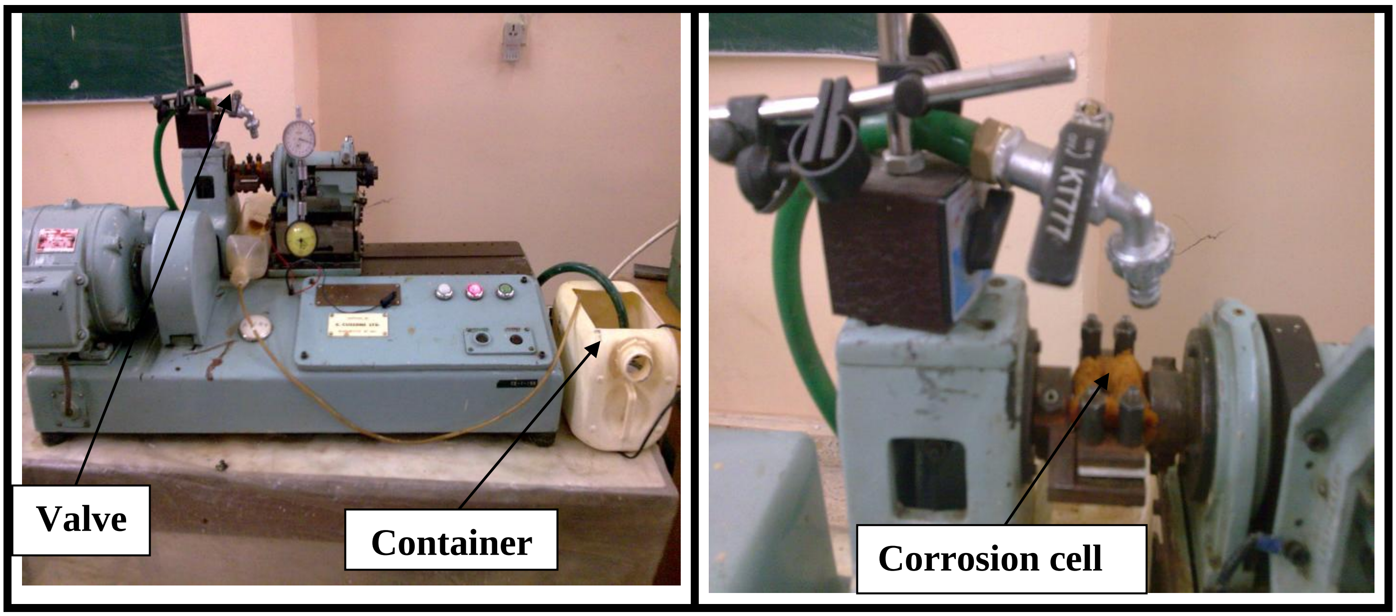

Figure (3): Shows the corrosion system attached to fatigue test rig

Results and discussion:

1- Constant Amplitude Fatigue Results:

The results obtained from the fatigue tests are given in table (3). The curves of stress amplitude versus number of cycles to failure (S-N) plotted using the above results are shown in figs. (4). Basquin s law may be used to express the relationship between the fatigue strength and fatigue life of the materials [8, 9]. This law is represented by an equation of the form.

$$\sigma_f = AN_f^{\alpha} \dots\dots\dots (1)$$

Where (σ_f) is the cyclic stress amplitude at failure, N_f is number of cycles to failure and (A), (α) are the fitting parameters. If this is so, then a plot of log N_f versus log σ_f will be a straight line, the slope of which will give the value of constant α.The constant A can be determined using the equation for this straight line. The data obtained from the fatigue tests were used to plot the graphs of the logarithm of fatigue life (log N_f) versus logarithm of stress amplitude (log σ_f) for the materials.

13 specimens were tested to find the basic S-N curve at room temperature. The experimental results are given in table (3)

Table (3): Basic S-N fatigue results at room temperature (RT):

Specimen No.	**Stress (MPa) σ_f**	**Nf (Cycles)**	**Nf (Cycles) Average**
1,2,3	230	1200,1000.900	1033
4,5,6	179	14000,15400,16000	15133
7,8,9	128	325000,335500,340000	333500
10,11,12	102	627000,540000,515000	560666
13	64	2500000	Unfailure

By plotting the applied stress at failure (σ_f) as a function of number of cycles to failure **(**Nf).the following equation can be obtained.

$$\sigma_f = 545N_f^{-0.12} \dots\dots\dots\dots (2)$$

The above empirical formula gives 79MPa fatigue strength at 10^7cycles.

2- Corrosion-fatigue test results:

To show the effect of environment on the fatigue behavior of the materials, the S-N curves obtained in air and salt water are given in figure (4). Comparison of the S-N curves obtained in salt water show that the fatigue life of materials is sensitive the corrosive environments. In addition, the materials had the longest fatigue life in air but the lowest in salt water. However, as the applied stress increases, the corrosive environments become less effective on the fatigue life of the materials. And as the number of cycles increases the corrosive environments become more effective on the fatigue strength of the materials

13 specimens were tested under fatigue-corrosion interaction using 3.5%NaCl solution. The results are given in table (4)

Table (4): Constant stress Fatigue-corrosion interaction results

Specimen No.	Stress (MPa) σ_f) (	N*f* (Cycles)	N*f* (Cycles) Average
14,15,16	230	960,900,1020	960
17,18,19	179	15500,15000,13800	14767
20,21,22	128	300000,297000,271800	289600
23,24,25	102	330000,319000,305000	318000
26	64	2500000	Unfailure

The best fit for the above data gives the following relation $\sigma_f = 560 N_f^{-0.125}$…… (3) and the fatigue strength at 10^7 is 75MPa.The fatigue and fatigue-corrosion behavior at constant stress amplitude is presented in figure (4)

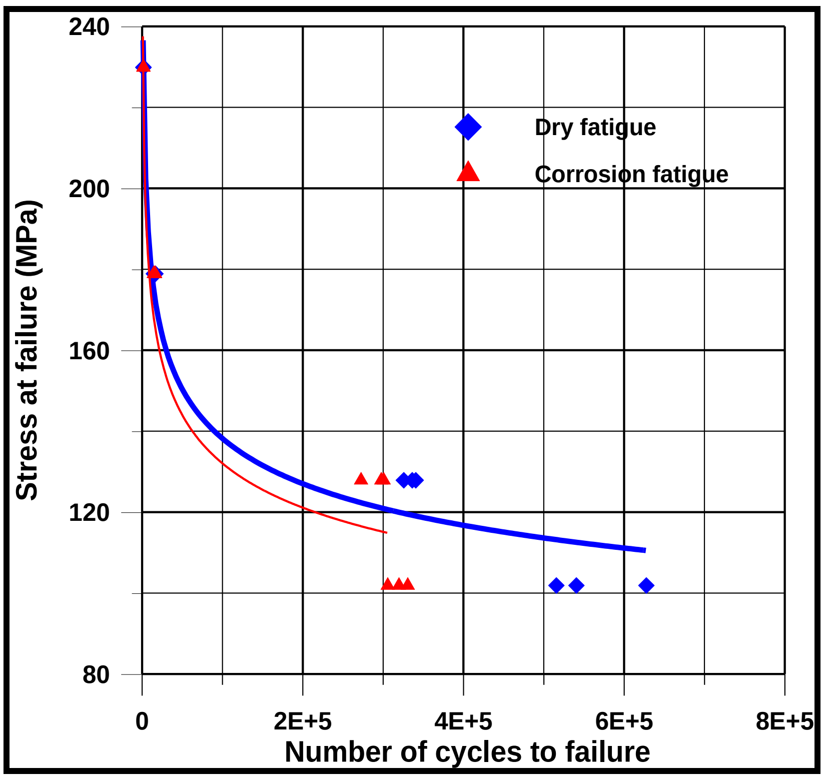

Figure (4): Fatigue and corrosion-fatigue behavior at constant loading for Aluminum (3003-H18) alloy.

From figure (4) it can be seen that the corrosion effects of the aluminum (3003-H18) alloy obtained at high cycles are in general higher than those obtained at low cycles. This is due to the fact that the corrosion becomes more effective as stress cycle or testing time increases.

Corrosion – cumulative fatigue damage results

The variable or cumulative amplitude loading fatigue tests with flat specimens were performed under two different loadings, i-e low stress and high stress using 3.5%Nacl as a corrosion environment. The experimental results are illustrated in table (5).

Table (5): Corrosion-cumulative fatigue damage results of 3003-H18 AL alloy

Specimen No.	Loading sequences (MPa)	Fatigue-corrosion life (cycles)	Average life (cycles)	Test program
27,28,29,30, 31	102-179	20800,31600,27000,18700, 26500	24920	179 MPa 102 MPa 10^4cycles
32,33,34,35, 36	179-102	19000,21600,23600,18000, 24600	21360	179 MPa 10^4 102 MPa 10^4cycle s

Discussion:

It is known that the corrosion fatigue takes place in three stages including surface pitting, crack formation, and crack propagation [10, 11]. The corrosion pits form in the first stage of fatigue act as stress concentration sites giving rise to crack formation and propagation [10, 12]. In aluminum alloys, aluminum oxide film forms on the surface and provides protection against corrosion [13]. This film is effective only for the PH range of 3-7 [14]. In the present work, the pH values of the environments were out of this range; therefore, it was not possible for the aluminum oxide film to provide enough protection. As a result, salt water was effective in reducing the fatigue life of the alloys.

Miners rule:

Among the several theories proposed for fatigue-life predictions, the Palmgren-Miner (PM) theory because of its simplicity seems to be the most widely used. Mathematically this theory may be written as [15]

$$\left(\frac{n_1}{N_{f_1}}\right)_{\sigma_1=constant}+\left(\frac{n_2}{N_{f_2}}\right)_{\sigma_2=constant}=1 \ldots\ldots\ldots(4)$$

Where n_1 is the applied number of cycles for σ_1

n_2 is the applied number of cycles for σ_2

N_{f1} is the number of cycle to failure at σ_1 (obtained from S-N curve)

N_{f2} is the number of cycle to failure at σ_2 (obtained from S-N curve)

it is important to note that the (PM) theory no provisions are made to take into account the various effects on fatigue life, such as the environment factor i-e the corrosion effects, and loading sequence effect low-high or high-low stress loading [16].

Proposed model

Aid et al [17] proposed a damage stress model (DSM) which is given by the formula:

$$D_{(DSM)}=\frac{\sigma_{equ}-\sigma_{i+1}}{\sigma_u-\sigma_{i+1}} \ldots\ldots\ldots(5)$$

Where σ_{equ}. is the equivalent stress of damage at the level $i+1$ and σ_{i+1} is the stress at the level $i+1$.σ_u is the ultimate stress of the material .The modified corrosion fatigue model (MCFM) presented in this paper based on Aid model and Marco-starkey (MS) [18] firstly proposed a nonlinear load dependent damage rule as follows

$$D_{MS} = \sum_{i=1}^{n} r_1^{x_i} \text{..........(6)}$$

Where x_i is a coefficient depending on loading sequence

For the current proposed model four factors affecting the corrosion-fatigue life.

These factors are:

1- Loading sequence (low-high and high-low)
2- Corrosion effect
3- Mechanical properties of test specimen material
4- Fatigue endurance limits

The modified corrosion fatigue model [MCFM] may be written as

$$D_{MCFM} = \left[\frac{\sigma_u - \sigma_{equ}}{(\sigma_f)_{Dry} - (\sigma_f)_{CF}} \right]^{Slope of CF(S-N) curve * \frac{\sigma_H}{\sigma_L}} \text{..........(7)}$$

Where σ_{equ} is the equivalent stress of σ_H and σ_l which can be found from the corrosion-fatigue S-N curve equation and for the present case σ_{equ} =111MPa.The application of the above equation to the data of table (5) may gives the form

$$D_{(MCFM)} = \left(\frac{205 - 111}{79 - 75} \right)^{-0.125 \times 1.755} = 0.5 \text{..........(8)}$$

Application of the modified corrosion –fatigue model (MCFM) gives a constant damage as in miner rule (PM),table (6) gives the corrosion-fatigue damage of specimen for three different cases, experimental, Miner rule and the modified corrosion fatigue model (MCFM)

The corrosion –fatigue life may be calculated according to the equation

$$N_f = (10^4 + 10^4) X \text{..........(9)}$$

Where x is the number of the programs until failure.

The values of x for the three cases are illustrates in table (7)

Table (6): Comparison of the (MCFM) and (PM) rule based on the experimental results

Corrosion – Fatigue lives , cycles		
D_{exp}	D_{PM}	D_{MCFM}
1.372	1	0.5
1.175	1	0.5

Table (7): The number of corrosion-fatigue programs until failure

X_{exp}	X_{PM}	$X_{(MCFM)}$
1.246 Low-high	0.908	0.454
1.068 High-low	0.908	0.454

The comparison of corrosion-fatigue life for three cases is illustrated in table (8)

Table (8): Comparison of corrosion-fatigue life for three methods

Loading Program	$N_{f\ exp.}$	$N_{f\ PM}$	$N_{f\ MCFM}$
Low-high (102-179)	24920	18160	10000
High-low (179-102)	21360	18160	10000

The MCFM is implemented to predict the fatigue life under the experimental conditions for variable amplitude loading. The proposed model presents lower deviation and the obtained results are more representative than those using (PM) concept. The proposed model correctly follows the experimental results provided in the literature taking into account the effect of loading history. It is based on the S-N curve and mechanical properties of the material used. The proposed model may be extended to different loading like increasing or decreasing. The results obtained from the MCFM can be compared with the experimental results and the estimated results are in good agreement with those compared .The factor of safety obtained by MCFM was 2.492 while PM gave 1.372 based on the experimental data.

Conclusions:

1- A modified damage (MCFM) based on the S-N curve and taking into account the effect of loading sequence is introduced in this study
2- The obtained results from (MCFM) are is good agreement with the experimental results
3- The corrosion solution reduces the fatigue endurance limit by 5.06% in comparison to dry fatigue
4- MCFM show 2.492 safety factor while PM gave 1.372 factor of safety based on the experimental life.

REFERENCES:

[1] C.E.Jaske, J.H. Payer, and V.S. Balint "**Corrosion fatigue of metals in marine environments**", springer-verlag, 1981.

[2] Ramsamooj D.V.and Shugar T.A. "**Modeling of corrosion fatigue in metals in an aggressive environment**" International Journal of Fatigue, 23 5301-5309 (2001)

[3] H.J. Mohammed AL-alkawi, H.B.Rahmatalla, H.Mohammed Kalld AL-juboury "**Corrosion fatigue behavior of 2024-T4 aluminum alloy**" Engineering and Technology Journal 1993

[4] Z.Khan "**Effect of Corrosive Environment on the Fatigue Crack Initiation and Propagation Behavior of AL 5454-H32**"Journal of Materials Engineering and Performance (1996).

[5] R.M. Chlistovsky, P.J.Heffernan , D.l. DuQuesnay " **Corrosion-fatigue behavior of 7075-T651 aluminum alloy subjected to periodic overloads**" International Journal of Fatigue, 29 1941-1949(2007).

[6] R.A. Siddiqui, S.A. Abdul-Wahab,T. Pervez "**Effect of aging time and aging temperature on fatigue and fracture behavior of 6063 aluminum alloy under sea water influence**" Materials and Design , 29 70-79 (2008).

[7] M.Shoeib, Y.Barakat "**Corrosion Fatigue of AZ91C Magnesium Alloy in Aqueous Solutions**" European Journal of Scientific Research Vol.42 No.1 PP.164-171 (2010).

[8]. Goodwin FE, Ponikvar AL. Engineering properties of zinc alloys. Reasearch Traingle Park (NC): ILZRO; pp.82-3, (1989).

[9]. Nagarjuna S, Srinivas M, Balasubramanian K, Sarnat DS. Effect of alloying content on high cycle fatigue behavior of Cu-Ti alloys. Int J Fatigue 45(3): 297-307, (1997)

[10]. Bayoumi MR. Fatigue behavior of a commercial aluminum alloy in sea water at different temperatures. Eng Fract Mech 1993; 45(3):297-307.

[11]. Dieter GE.Mechanical metallurgy.New York:Mc-Graw Hill;1976. P.210-16, 433.

[12]. Pokhmurskii VI.General aspects of corrosion fatigue in metals and alloys.Proceedings of the first USSR-UK Seminar on corrosion fatigue of metals, Lvov,May 1980.London: the Metal Society; (1983).p.47-53.

[13]. Avner SH. Introduction to physical metallurgy.New York: Mc-Graw Hill; (1974).p.493-4.

[14]. Jones DA. Principles and prevention of corrosion. USA: Pren-tice-Hall; 1996.p.357-9.

[15]. K.J. Miller, H.J.Mohammed Alalkawi ,E.R.de los Rio "**Fatigue damage accumulation above and below the fatigue limit** "mechanical engineering , London pp 491-511 (1986).

[16]. Alalkawi, H.J.M., Aljubory K.Hamid, Alsalihy Huda, A." **Fatigue damage accumulation behavior of 2024-Al-alloy under the effect of shot peening time**" J.of Engineering and Technology Vol.25, No.5 (2007).

[17]. A.Aid, A.Amrouche,B.Bachir,M.Benguediab,G.Mesmacque "**Fatigue life preduction under variable loading based on a new damage**" Material and Design 32,183-191(2011).

[18]. Marco S M,starkey WL."**A concept of fatigue damage**" Trans. ASME, 76,627-32 (1954).