Thermo-Mechanical Fatigue (TMF) Behavior of Three Different Steel Alloys

Dr. Hussain J. Mohammed Al-Alkawi
Electromechanical Engineering Department, University of Technology/Baghdad
Dr. Mohammed H. Ali
Collage of Engineering, University of Al-Mustansiriya/ Baghdad
Shaimaa Ghazy Mezban
Collage of Engineering, University of Al-Mustansiriya/ Baghdad

Received on: 13/10/2016 & Accepted on:24/11/2016

ABSTRACT
This paper presents the effect of temperature on the fatigue properties of carbon steel containing three different content of carbon: 0.758%C, 0.539%C and 0.319%C. The tests were conducted at room temperature and at variable temperatures. The temperature cycle used was in the range from 50^{o}C to 100^{o}C and 150^{o}C respectively. Using constant amplitude loading, the fatigue test was done by rotating bending machine. The results obtained from the fatigue test at room temperature were compared with the fatigue test results at variable temperatures. A modified Miner rule was applied to predict the fatigue life at variable temperatures and to evaluate the fatigue damage in every steel alloy. The fatigue damage was determined as the number of cycles and stress. The results showed that the alloy steel with 0.539%C had the best resistance to the constant applied load and variable temperature and it was also found that the fatigue life of all three alloys decreased at variable temperature compared to room temperature.
Keywords: thermal cycling; variable temperature cycles; carbon steel alloy.

INTRODUCTION
Fatigue is defined as a progressive damage process of a component subjected to repeated load. It consists of nucleation of cracks and then their propagation until fracture of the component occurs. Localized plastic deformation takes place at stress concentrated sites leading to development of cracks and damage of the component. The length of the crack increases with increasing number of loading cycles, so the crack will cause the component to fail after a certain number of cycles. It is estimated that fatigue failure is responsible for 90% of service failures where the material fails below yield stress [1]. Steels are widely used in industry as structural materials because they possess good soft-magnetic properties, high strength, low material cost and good resistance to wear and corrosion [2]. Among steels, carbon steels are the most widely used material in the industry. It is divided into low carbon steel containing too little carbon below 0.15%C, medium carbon steel with a carbon content of 0.25 to 0.55%C and high carbon steel with carbon content greater than 0.55%C [3]. The effect of carbon percentage on mechanical properties has been studied. It has been shown that the elongation is reduced with increasing carbon content but the hardness of the steel is increased. A survey conducted by A. Calik et.al (2010) to study the relationship between the carbon content and mechanical properties of medium carbon steels at room temperature with a carbon content from 0.30 to 0.55 by tensile and micro-hardness tests. It has been seen that the strength increases but the elongation decreases with increasing carbon content and

https://doi.org/10.30684/etj.34.15A.5
2412-0758/University of Technology-Iraq, Baghdad, Iraq

both σ_y and σ_{UTS} have a linear relationship with carbon content and increase significantly with increasing the carbon content. Q. Bader and E. Kadum (2014) estimated the fatigue life of three different carbon steel alloys. Results showed that fatigue limit at room temperature increases with increasing hardness and carbon content [4]. A carburizing process study showed that reduction in case carbon content from 1.2%C to 0.6%C results in less retained austenite, higher compressive residual stresses at the surface leading to improvement in the endurance limit of carburized steels [5].

Thermal fatigue

Thermal fatigue is a damage process of components as a result of multiple cycle and periodic changes in the temperature. Therefore the component undergoes changes in physical properties and geometry leading to initiation of cracks. Jung-Ho Moon and Tae Kwon HaIn (2014); evaluated the thermal fatigue properties of 304, 310S, and Xm15J1 austenitic stainless steels in the temperature ranges of 200-800^{o}C and 200-900^{o}C. The minimum temperature was 200^{o}C in all cases and the maximum temperature was taken as 800^{o}C and 900^{o}C. The results showed that thermal fatigue property of stainless steel alloy 304 was superior to that of the other 300 series stainless steels [6]. A complex damage may result when the thermal transients is combined with mechanical load cycles after a certain number of cycles of the component resulting in thermo-mechanical fatigue of the material [7]. Hong Tae Kang et.al (2007); studied fatigue damage under variable temperature and loading amplitudes for automotive exhaust systems at temperatures range: 90, 180, 270, 360, 450 and 540ºC. It was found that the total damage for thermo-mechanical variable loads and temperatures is caused by both oxidation and mechanical damage [8]. The objective of this study is to evaluate the effect of variable temperature cycles on the fatigue life of carbon steel with three different carbon contents taking the effect of carbon percentage into account.

Experimental method

The chemical composition of the carbon steel used in this study was analyzed. Tensile tests were carried out on a standard specimen at room temperature for their ultimate strength and yield strength. These parameters obtained from the standard tensile testing are useful for the selection of engineering materials for any applications required. Finally, the fatigue test at room temperature and high temperature were performed using variable temperature cycles. All fatigue tests were performed at 1400 rpm (23.34 Hz).

Chemical analysis

Three different carbon steel alloys with different carbon contents were selected as a material in this study. The chemical compositions of the tested material are listed in Table 1 for each group of carbon steel which was carried out at (State Company for Inspection and Engineering Rehabilitation (SIER) in Iraq). The mechanical properties of carbon steel evaluated from the tensile test are summarized in Table 2.

Table 1 Chemical composition of three groups of carbon steel

AISI No.	Standard ASTM A 29/A 29M-05 [9]			
	C%	Mn	$P_{max.}$	$S_{max.}$
(A)1075	0.70-0.80	0.40-0.70	0.04	0.05
(B)1053	0.48-0.55	0.70-1.00	0.04	0.05
(C)1030	0.28-0.34	0.60-0.90	0.04	0.05
AISI No.	**Experimental Chemical Composition**			
	C%	**Mn**	**P**	**S**

A	0.758	0.297	0.0006	0.006
B	0.539	0.623	0.006	0.001
C	0.319	0.607	0.002	0.001

Table 2 Mechanical properties of carbon steel

AISI No.	C%	Ultimate Stress σ_u, [MPa]	Yield stress σ_y, [MPa]	Elongation [%]	Modulus of elasticity (E)[GPa]
1075	0.758	820	480	26.5	205
1053	0.539	691	377	38.4	204
1030	0.319	804	462	27.79	207

Fatigue test

A fatigue fracture experiment may take many hours and the procedure sets up and starts for a number of specimens. Cylindrical fatigue specimens were provided according to the Machines Manual as shown in Figure 1. The shape of the fatigue specimens is hour-glass type in order to obtain stress concentration in the middle of the specimen (the minimum diameter). Fatigue test was carried out until complete fracture of the specimens occurred using the fatigue testing machine Schenck product of type PUNN rotating bending. At all tests, crack initiation and fracture occurred at the mid-point of the specimens shown in Figure 2. The tests were done at University of Technology Electromechanical Engineering Department.

Figure(1) Fatigue test specimen according to (DIN 50113) standard specification with dimensions in millimeter

Figure (2). Fatigue test specimen after fracture.

Thermal fatigue experiments were carried out with the use of a furnace to heat the environment surrounding the specimens to the required temperature. Figure 3 shows the furnace attached to the fatigue testing machine. The walls of the furnace are made of two layers of steel plate with 3mm thickness for each layer and well insulated. A K-type thermocouple is used which is conducted to a digital thermostat to control the heating temperature inside the furnace and to measure the temperature of the heater. It is a low cost device and one of the most popular thermocouples. The thermocouple is attached to the thermal control unit board and the furnace.

Figure (3) Furnace attached to fatigue machine.

Experimental results and discussion
Fatigue test results at room temperature

Two set of fatigue tests were performed .The first one was carried out at room temperature and no temperature dependent behavior of the specimen was introduced. The results of the fatigue test at room temperature including the number of specimens used, applied stresses and number of cycles are presented in table 3. The second one was carried out at different temperature ranges which will be described later.

Table 3 Fatigue test results at room temperature.

Specimen No.	Applied Stress (MPa)	N_f Cycles
	0.758%C	
1,2,3	500	2000, 3000, 1300
4,5,6	400	11000, 9500, 12500
7,8,9	300	52000, 62000, 44000
10,11,12	200	395000, 410000, 366000
	0.539%C	
13,14,15	500	1200, 2000, 3000
16,17,18	400	7000, 10000, 11000
19,20,21	300	116000, 122000, 130000
22,23,24	200	420000, 380000, 460000
	0.319%C	
25,26,27	500	10000, 12000, 14000
28,29,30	400	19000, 22000, 26000
31,32,33	300	140000, 125000, 110000
34,35,36	200	320000, 290000, 370000

The S-N curve is a graphical representation of fatigue data. It represents the relationship between the stress applied and the number of cycles to failure. The most commonly used model which provides an analytical expression of the S-N curve for high or low cycle fatigue is Basquin relation. An estimation of fatigue life prediction can be obtained by using this technique.

$$\sigma_a = a\, N_f^{\,b} \qquad \ldots (1)$$

Where σ_a is the fatigue stress amplitude (MPa) and N_f is the number of cycles to failure. The parameters a and b are constants and depend on material and geometry. The coefficient a, is equal to the tensile strength and the coefficient b is the fatigue strength exponent. These coefficients are evaluated by least square method (linearizing the power law in logarithmic form) [10]. The above data are plotted according to Basquin equation and Figure 4 shows the behavior of the three carbon content alloys.

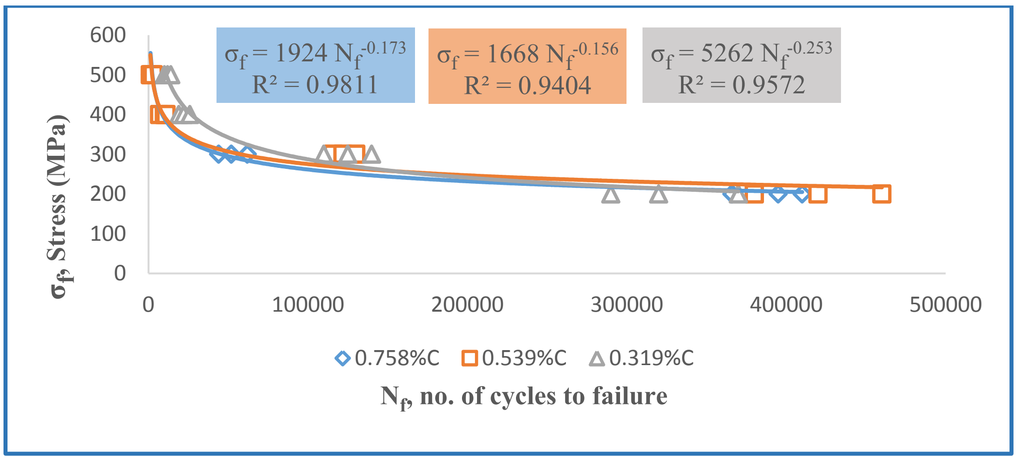

Figure (4) S-N curve for three groups at room temperature

Fatigue test results at variable temperature

Referring to Ref. [11], thermal fatigue test was performed at constant temperature (100°C). In this study, we perform thermal fatigue test at variable temperature cycles. In this case, the specimens were exposed to temperature in a variable cycling manner. The temperature cycles used was in the range from 50°C to 100°C and 150°C respectively. Three stress levels were applied 350MPa, 300MPa and 200MPa for each group using three specimens to be tested at each of those three stress levels. Starting the test at room temperature, fatigue testing machine was turned on and the specimen was heated until 50°C is reached then the machine was turned off after 1000 cycles and it was turned on again until 100°C and then turned off after 1000 cycles. The same work was repeated for the temperature of 150°C and the procedure was repeated many times for the three temperatures in a cyclic way. The diagram of the variable temperatures used for this test is illustrated in Figure 5 and Table 4 gives the results of S-N curves data at variable temperature for each group of carbon steel alloys.

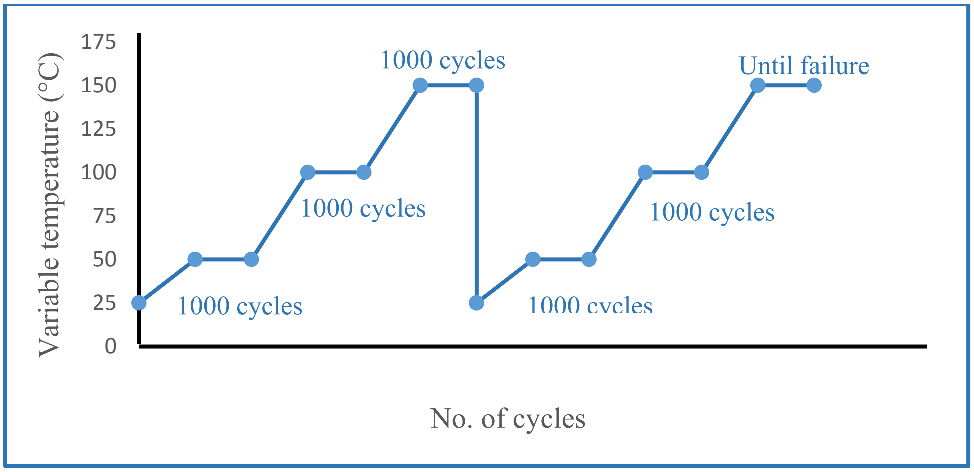

Figure (5) Schematic diagram for variable temperature constant stress amplitude fatigue test

Table (4) Variable temperature S-N curve results and Basquin equations

AISI No.	C%	Applied stress (MPa)	N_f Cycles	Basquin formula
(A) 1075	0.758	350 300 200	23000, 19000, 21000 40000, 38000, 30000 222000, 194000, 214000	$\sigma_f = 3665\ N_f^{-0.237}$
(B) 1053	0.539	350 300 200	82000, 66000, 83000 130000, 119000, 138000 305000, 341000, 329000	$\sigma_f = 27690\ N_f^{-0.387}$
(C) 1030	0.319	350 300 200	69000, 59000, 64000 119000, 98000, 104000 277000, 288000, 278000	$\sigma_f = 23624\ N_f^{-0.379}$

Fatigue life prediction at variable temperature according to modified Miner rule

Following the work of Miller et al [12], they proposed a model based on Miner rule for increasing stress amplitude and the prediction results were satisfactory for predicting fatigue life in continuously increasing stress amplitude situation. The model can be written in the form:

$$\sum\left(\frac{1}{N_f}\right)_i = \frac{1}{\alpha}\int_{\sigma_{F.L}}^{\sigma_f}\frac{1}{N_{fi}}d\sigma_{fi} = 1 \quad \ldots(2)$$

For the present modified Miner rule, the linear damage is not equal to unity but equal to damage and it can be calculated from equation (3) below:

$$\sum\left(\frac{1}{N_f}\right)_i = \frac{1}{\alpha}\int_{\sigma_{F.l}}^{\sigma_f}\frac{d\sigma_i}{N_{fi}} = damage \quad ..(3)$$

The S-N curve equations for the present work are:

$\sigma_f = 3665\ N_f^{-0.237}$ for A1075

$\sigma_f = 27690\ N_f^{-0.387}$ for B1053

$\sigma_f = 23624\ N_f^{-0.379}$ for C1030

From the above equation:

$\frac{1}{N_f} = (\frac{\sigma_f}{constant})^{H_1}$ for A1075

$$\frac{1}{N_f} = \left(\frac{\sigma_f}{constant}\right)^{H_2} \quad \text{for B1053}$$

$$\frac{1}{N_f} = \left(\frac{\sigma_f}{constant}\right)^{H_3} \quad \text{for C1030}$$

Where H is an experimental coefficient of S-N curve at variable temperature and α is the temperature rate.

Table 5 Results of damage and life of each group of carbon steel according to Miner rule.

Stress (MPa)	Results obtained from Miner rule model	A1075	B1053	C1030
350	Damage	0.0336	0.0014	0.002
	R	0.0225	0.0037	0.0044
	$N_{f\ model\ (cycles)}$	675	111	132
300	Damage	0.0184	0.001	0.0014
	R	0.0236	0.0039	0.0047
	$N_{f\ model}$	708	117	141
200	Damage	0.004	0.0004	0.00053
	R	0.0284	0.0045	0.0051
	$N_{f\ model}$	852	135	153

Table 5 shows values of damage (D), number of programs (R), and fatigue life time predicted according to Miner theory. It is clear that all the above values are lesser than that of actual values and these insufficiencies may be due to the followings which mentioned by many researchers [13]:

1- Miner rule does not take into consideration the effect of environment. Example the temperature, treatment of the surface like shot peening, laser and corrosion.

2- The lack of take account of damage below the fatigue limit.

3- The lack of loading levels interaction.

All the above reasons lead to non-conservative prediction of Miner rule.

Comparison between the experimental fatigue lives and Miner prediction can be seen in Table 6.

Table (6) Comparison between fatigue lives for experimental and Miner prediction

Applied stress (MPa)	A1075		B1053		C1030	
	Experimental N_f	Miner N_f	Experimental N_f	Miner N_f	Experimental N_f	Miner N_f
350	20109	675	80369	111	66935	132
300	38534	708	119696	117	100521	141
200	213197	852	341272	135	292947	153

Figure 6, Figure 7 and Figure 8 show a comparison of S-N curves experimentally and according to Miner rule for each group of carbon steel alloy respectively.

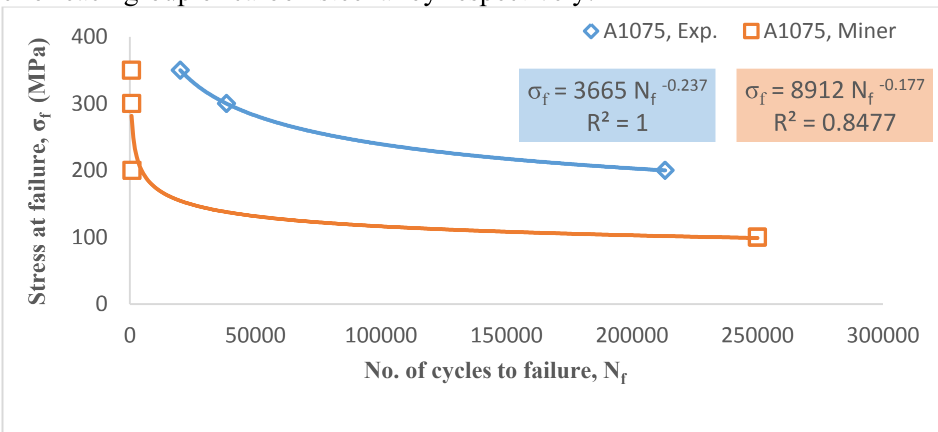

Figure (6) S-N curves experimentally and according to Miner rule for A1075 alloy.

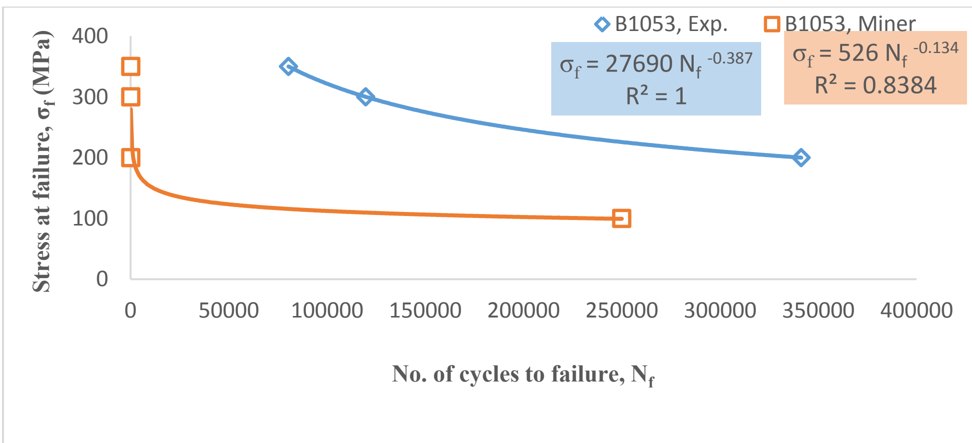

Figure (7) S-N curves experimentally and according to Miner rule for B1053 alloy.

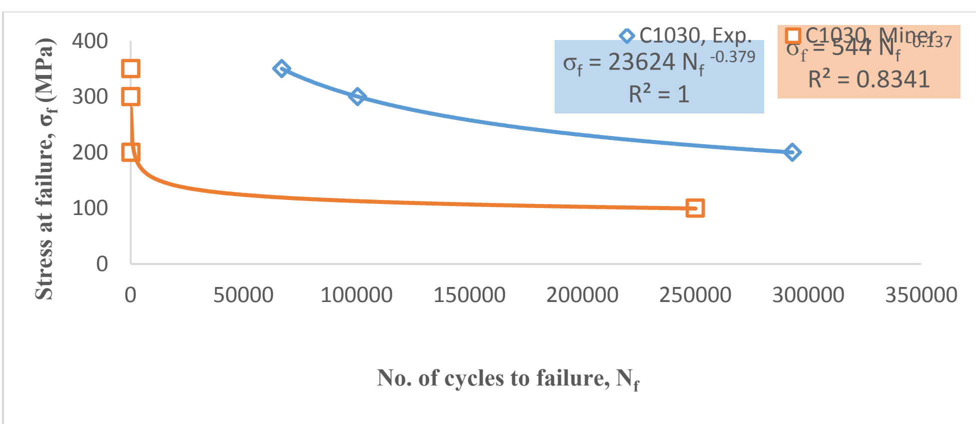

Figure (8) S-N curves experimentally and according to Miner rule for C1030 alloy.

Many workers tried to improve the linear damage rule (Miner) but due to its intrinsic shortcomings, no matter which version is used, fatigue life estimation depend on the above theory is often unsatisfactory [14,15].

CONCLUSIONS

The fatigue Characterization of three different carbon percentage steel alloys was studied experimentally at room temperature and variable high temperature. The following remarks may be derived from this work.

1. Fatigue lives of the three alloys, namely A1075, B1053 and C1030 were reduced at variable temperature compared to room temperature testing results.
2. Experimental results revealed that the B1053 steel alloy with 0.539% carbon percentage was the best alloy in resisting the constant applied load and variable temperature.
3. A modified linear damage rule was adopted based on Miner rule but without damaging equal to unity. The application of the above model gave unsatisfactory prediction compared to the experimental life results.
4. The S-N curves obtained experimentally and based on modified Miner rule were established and the modified S-N curve was shown to be underestimated the fatigue properties of the three alloys mentioned above.

REFERENCES

[1] Agrawal R., Uddanwadiker R., Padole P.,"Low cycle fatigue life prediction", International Journal of Emerging Engineering Research and Technology. vol. 2, Issue 4, pp.5-15, 2014.

[2] Calika A., Duzgunb A., Sahinc O., Ucard N.,"Effect of carbon content on the mechanical properties of medium carbon steels", A Journal of Physical Sciences, vol. 65, Issue 5, pp.468-472, 2010.

[3] Gandy D. Carbon Steel Handbook. Electric Power Research Institute Inc, 2007.

[4] Bader Q., Kadum E.,"Mean stress correction effects on the fatigue life behavior of steel alloys by using stress life approach theories", International Journal of Engineering & Technology IJET-IJENS, vol.10, p50, 2014.

[5] Wise J.P., Krauss G., Matlock D.K.,"Microstructure and fatigue resistance of carburized steels", 20th ASM Heat Treating Society Conference Proceedings, ASM International, pp.1152 – 1161, 2000.

[6] Moon J.H., Ha T.K.,"Thermal fatigue behavior of austenitic stainless steels", International Journal of Chemical, Molecular, Nuclear, Materials and Metallurgical Engineering, vol.8, No.5, pp.388-391, 2014.

[7] Seifert T., Schweizer C., Schlesinger M., Moser M., Eibl M.,"Thermo-mechanical fatigue of 1.4849 cast steel experiments and life prediction using a fracture mechanics approach", Int. J. Mat. Res., pp.942-950, 2010.

[8] Kang H.T., Lee Y.L., Chen J., Fan D.,"A thermo-mechanical fatigue damage model for variable temperature and loading amplitude conditions", International Journal of Fatigue, vol.29, pp.1797–1802, 2007.

[9] Standard specification for steel bars, carbon and alloy, hot wrought, general requirements, Designation: ASTM A29/A 29M-05 EDT, 2006.

[10] Schijve J. Fatigue of Structures and Materials. Springer, Second Edition, 2009.

[11] Al-Alkawi H.J., Ali M.H., Mezban S.G., " Elevated temperature fatigue S-N curve behavior for three different carbon percentage steel alloys", International Energy and Environment Foundation (IEEF), 2076-2895, 2016.

[12] Miller K.J., Mohamed H.J., de los Rios E.R.,” Fatigue damage accumulation above and below the fatigue limit”, The behavior of short fatigue cracks, EGF Pub.1 (Edited by K.J. Miller and E.R. de los Rios), Mechanical Engineering Publications, pp.491-511, 1986.
[13] Aid A., Amrouche A., Bachir B., Benguediab M. Mesmacque G.,“Fatigue life prediction under variable loading based on a new model”, Material and design, vol.32, pp.183-191, 2011.
[14] Dattoma V., Giancane S., Nobile R., Panella F.W.,“Fatigue life prediction under variable loading based on a new non-linear continuum damage mechanics model”, Int. J. Fatigue, 28(2), pp.89-95, 2005.
[15] Masahiro J.,“Fatigue damage and crack growth under variable amplitude loading with reference to the counting methods of stress-strain ranges”, Int. J. Fatigue, 27, pp.1006-1015, 2005.