Linear Damage Rule Life Prediction For Stress Controlled Fatigue-Creep Interaction of Aluminum Alloys

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ABSTRACT

The fatigue-creep interaction performance of 5086 and 6061-T651 aluminum alloys were investigated for specimens tested under control stress rotating bending at a stress ratio R=-1 and 250°C temperature. The fatigue endurance limit for both alloys reduced at 250°C.

The fatigue and creep damage was evaluated based on the linear damage rule, where the fatigue damage was determined as the number of cycles to failure and the creep damage was evaluated based on the time applied experimentally for low to high and high to low amplitude stress. The cumulative fatigue-creep interaction damage was found to around 0.5 i.e DF $+D_c$ =0.5

Fatigue – creep interaction lives predicted by the linear damage rule were compared to the actual lives. The results show that the linear damage rule gave an overestimated predictions.

Keywords: Stress controlled fatigue creep interaction, life prediction, linear damage rule, aluminum alloys.

تخمين عمر الضرر الخطي للاجهاد المسيطر لتداخل الكلال والزحف لسبائك الالمنيوم

الخلاصة

تم بحث أداء تداخل الكلال مع الزحف لسسبيكتي الالمنيوم 5086 و 6061-T651 لعينات فحصت تحت سيطرة الاجهاد والانحناء الدوار بنسبة اجهاد R=-1 ودرجة حرارة 250 °C . تم تقييم ضرر الكلال الزحفي اعتماداً على قاعدة الضرر الخطية حيث ان ضرر الكلال استخرج كعدد دورات لحد الفطل وضرر الزحف اعتمد على زمن التسليط العملي للاجهادات من واطىء-عالي وعالي واطىء . تداخل الضرر التراكمي للكلال والزحف وجد عند حوالي 0.5 حيث ان $D_f + D_c = 0.5$. تم تخمين اعمار تداخل الكلال الزحفي بواسطة قاعدة الضرر الخطية وقورنت مع الاعمار الحقيقية وبينت النتائج ان تخمينات القاعدة الخطية كانت أعلى بكثير من النتائج العملية.

الكلمات المرشدة : تداخل الكلال والزحف تحت السيطرة على الاجهاد ، تخمين العمر ، قاعدة الضرر الخطية ، سبائك الالمنيوم .

INTRODUCTION

Material properties are dependent on the temperature. The tensile strength, yield strength and modulus of elasticity decrease with increasing temperature. The effect of high temperature on mechanical properties can be associated with transformations of material structure due to diffusion processes, aging, dislocation restricting (softening) and recrystallization. In general, such processes imply that plastic deformation can occur more easily at an elevated temperature. This can lead to the well-known creep phenomenon [1].

High-temperature fatigue combined with time-dependent temperature variations applies to specific structures. As an example, turbine blades are exposed to high combustion temperature, high centrifugal forces and vibratory bending loads. High-temperature fatigue conditions imply that the fatigue load and temperature vary both as a function of time. In add to cyclic load, two more variables are time (t) and temperature (T). it then is easily recognized that the complexity of the problem scenario in practice can be considered [2].

Creep- fatigue interaction has been studied by many investigators [3-6]. As an example lifetime prediction in Creep- fatigue environment has been studied by Sabour [7] and innovative mathematical models are proposed to predict the operating life of aircraft components, specifically gas turbine blades subjected to Creep- fatigue at high temperature.

Several damage rules have been suggested for estimating the cumulative damage under creep-fatigue conditions [8-10]. There are divergent opinions regarding which damage approach provides the best basis for life prediction; however, the overall objective of all approaches is to secure a life prediction methodology.

The results of the fatigue limit of various materials as affected by temperature were collected by Forrest [11], see fig. (1). The data were obtained under cyclic bending at frequencies in the order of 40 to 50 Hz. For several materials, the fatigue-limit above a certain temperature is considerably reduced, which indicates that the material can no longer be used at higher temperatures. A comparison between different materials in fig. (1) indicates a relatively high-fatigue strength of Ti-alloy at temperatures up to about 400°C. Ti-alloys are still used for several high-temperature applications, particularly in several components of turbofan engines. Fig. (1) also shows that the austenitic steel are superior to the martensitic steel.

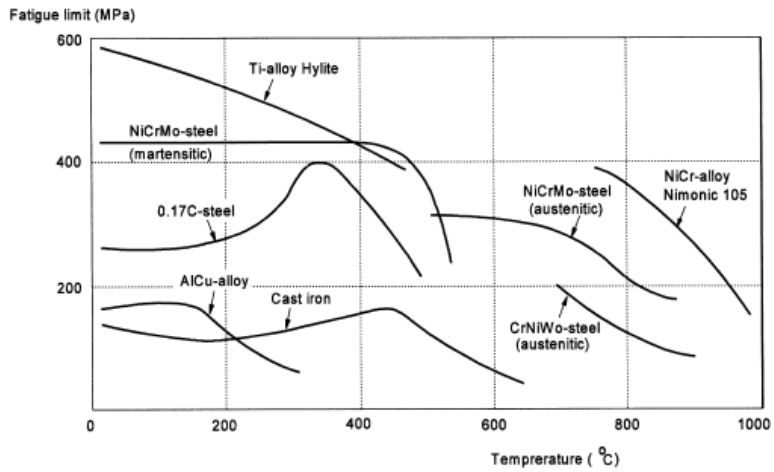


Figure (1); The influence of the temperature on the fatigue limit ($N=10^7$) of various materials. [11]

A remarkable behavior is exhibited by the 0.17C steel (mild steel). The fatigue limit apparently increases at elevated temperature until a maximum of about 350°C. According to Refs [11]&[12], this should be associated with strain aging due to enhanced diffusion of carbon atoms to dislocations which then are restricted in slip movements. The reduction of the fatigue limit of the aluminum alloy (Al-Cu) at elevated temperature is a result of overaging of the precipitation hardened material structure.

In this paper, a series of dry fatigue and fatigue-creep tests of two different aluminum alloys have been carried out at stress ratio R=-1 and under rotating bending loading. The elevated temperature was 250°C for all fatigue-creep testing. This work examines the effect of temperature on the fatigue endurance limit of two different aluminum alloys namely 6061-T651 and 5086.

MATERIALS AND EXPERIMENTAL PROCEDURE

The materials 6061-T651 and 5086 which are widely used in airplanes, turbine blades and many industrial application.

CHEMICAL COMPOSITIONS

Chemical analysis of the above alloys was conducted at the Specialized Institute for Engineering Industries using X-rays method. The results, with the standards, are illustrated in Table (1).

Table (1) Chemical compositions for selected aluminum alloys

Al. alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Al
5086 Standard	0.4	0.5	0.1	0.2-0.7	3.5-4.5	—	0.25	Rem
5086 experimental	0.38	0.51	0.09	0.45	3.9	0.02	0.26	Rem
6061 Standard	0.4-0.8	0.7	0.15-0.4	0.15	0.8-1.2	0.04-0.35	0.25	Rem
6061 experimental	0.62	0.71	0.35	0.102	0.95	0.2	0.18	Rem

MECHANICAL PROPERTIES

Three monotonic tests are carried out for each metal. The results of testing are the average of three readings. Table (2) gives the experimental with the standard values according to DIN 50123.

Table (2) Standard and experimental mechanical properties

Al. alloy	**Ultimate strength (Mpa)**	**Yield strength (Mpa)**	**Elongation %**	**Modulus of lasticity (Gpa)**
5086 standard	**260**	**115**	**22**	**71**
5086 Experimental	**265**	**121**	**21**	**73**
6061-T651 standard	**310**	**275**	**12**	**69**
6061-T651 Experimental	**365**	**307**	**13**	**70**

SPECIMEN PREPARATION

All specimens are manufactured according to DIN 50113 using CNC lathing machine. Then all the specimens machined, according to the profile of the copy machining. The test specimen shown in figure (2).

FATIGUE TESTING MACHINE

A fatigue testing machine of type PUNN rotating bending is used to test all fatigue specimens, with constant and variable loading, as shown in fig. (3)

The rotary bending stress (σ_b) was calculated according to the following equation [13]:-

$$\sigma_b = \frac{32*125.7P}{\pi*d\wedge 3} \qquad \text{….. (1)}$$

where the force arm is equal to 125.7 mm, d is the minimum diameter of the specimen 6.67 mm, P is the load applied in Newton and σ_b in Mpa.

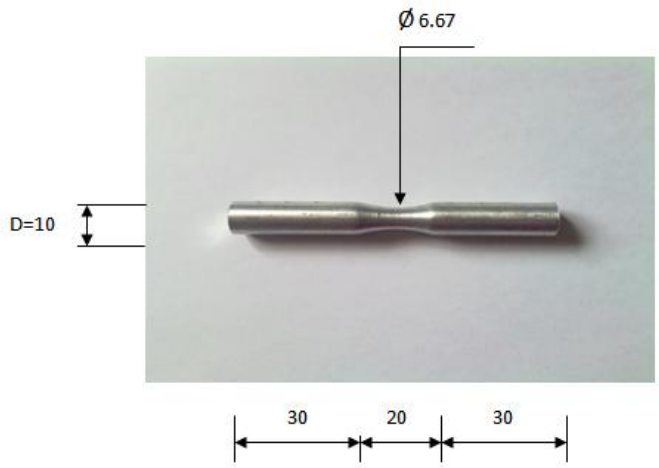


Figure (2): geometry of fatigue and fatigue-creep interaction specimens; all dimensionsin millimeter according to (DIN 50113) standard specification

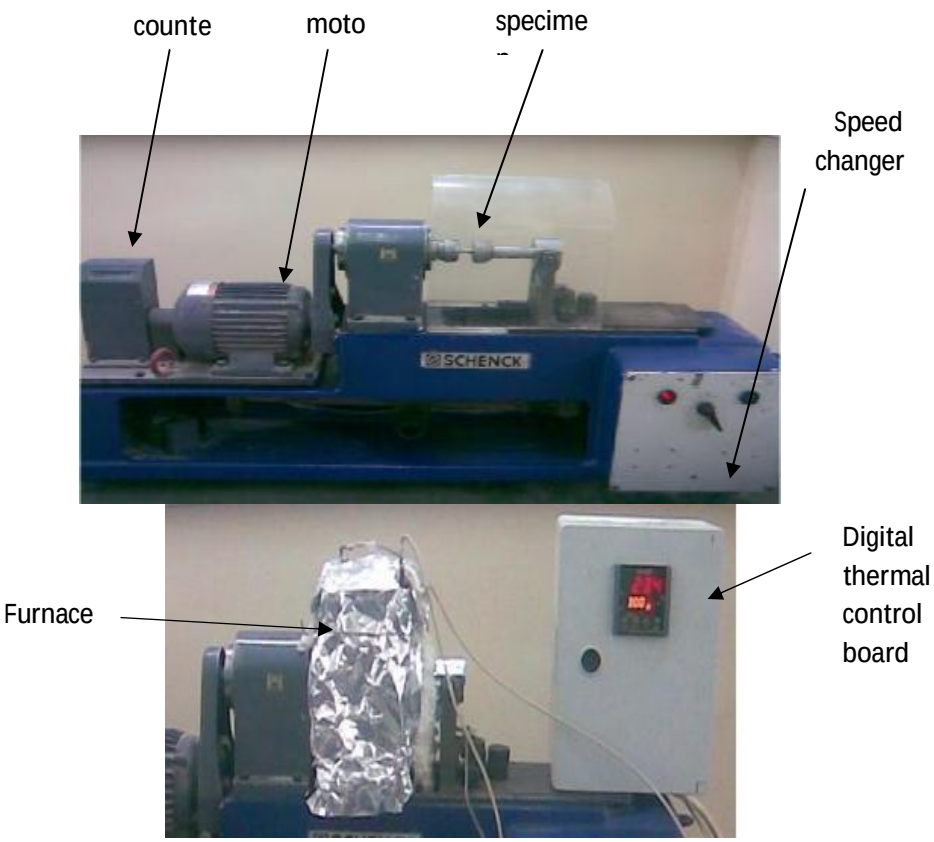


Figure (3): PUNN Rotary fatigue bending machine.

FATIGUE-CREEP TESTING MACHINE

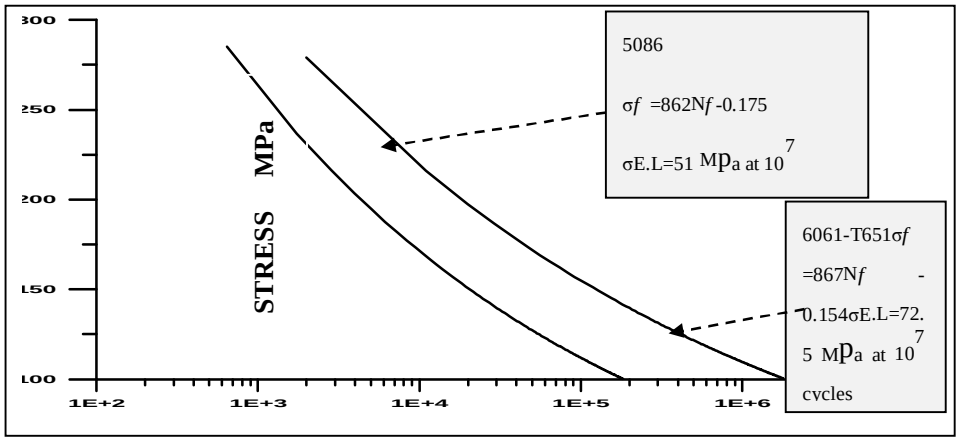
A small furnace is required to heat the specimen to a known elevated temperature. Thus, an elevated furnace is designed and made with suitable dimensions of ($10\times12\times140$ mm^3). The furnace can be attached to the fatigue testing machine. A digital thermal control unit board was designed and manufactured for this purpose. The fatigue-creep testing machine can be seen in fig. (4). More details of this machine can be seen elsewhere [14].

EXPERIMENTAL RESULTS AND DISCUSSION

Failure was defined as the point of instability, i.e. at the instant when the load bearing capacity of a structure or specimen begins to decay rapidly and the test stopped.

Test series one

36 specimens were tested for each metal to provide base line data over the fatigue regime of 10^3 to 10^7 cycles to failure, see fig. (5) and table (3).



No. of Cycles to failure, N_f

Figure (4); S-N curve for 5086 and 6061-T651 Al. alloys at Room temperature

Test series two

28 specimens were tested at 250°C, 14 specimens for each metal, the base line data (S-N curves) can be seen in fig(6) and table (4). This table gives the results of endurance limit at 10^7cycles as affected by temperature. This effect is observed by the reduction percentage in endurance limit as shown in fig.(6).

Table (5) shows the fatigue endurance limit stress at 10^7 cycles. This endurance limit is a threshold value of stress amplitude. Stress amplitudes below this level do not lead to failure, while stress amplitudes above this level lead to crack initiation and crack growth to failure [15]. For structures subjected to variable loading in service, it may be desirable that fatigue failures should never occur. It implies that all load cycles of the load spectra should not exceed this level [16].

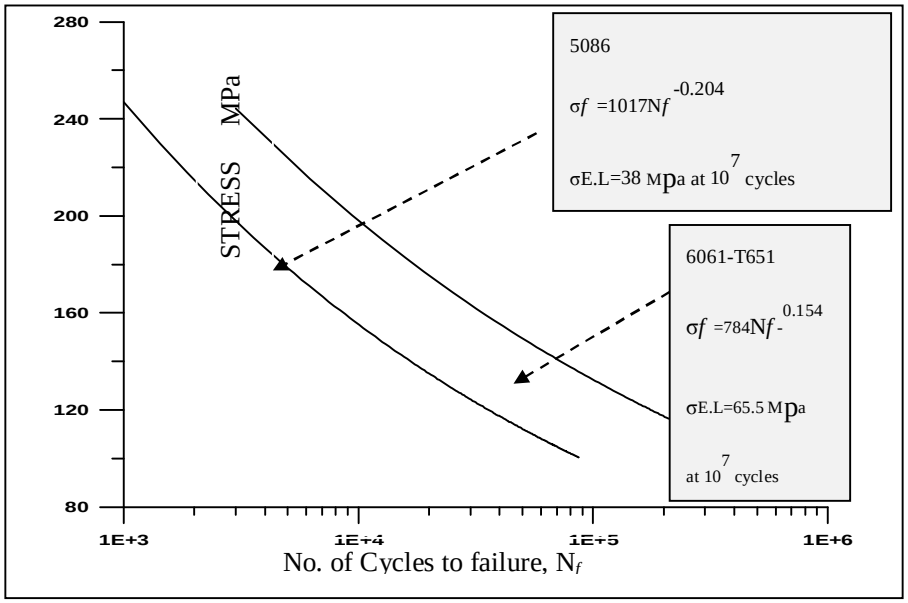


Figure (5); S-N curve for 5086 and 6061-T651 Al. alloys at 250 °C

Table (5): S-N curves equations and fatigue limits for the selected aluminum alloys.

Al.alloys	$\sigma_f=A.N_f^{\alpha}$ At room temp.	$\sigma_f=AN_f^{\alpha}$ At 250 c^o	$\sigma_{E.L}$ at 10^7 At room temp. Mpa	$\sigma_{E.L}$ at 10^7 At 250 c^o Mpa	$\sigma_{E.L}$ Reduction %
5086	$\sigma_f=862N_f^{-0.175}$	$\sigma_f=1017N_f^{-0.204}$	51	38	25.5
6061-T651	$\sigma_f=867N_f^{-0.154}$	$\sigma_f=784N_f^{-0.154}$	72.5	65.5	9.5

TEST SERIES THREE (CUMULATIVE FATIGUE-CREEP DAMAGE TESTS)

12 two-level cumulative damage test were perform at 250 °C to determine cumulative damage summation factors over a wide range of low stress range amplitudes. Table (6) gives these results.

It was noted previously that rigorous predictions starting from fatigue data for unnotched specimens can not be made, but empirical equations have been proposed which may lead to reasonable estimates of the endurance fatigue limit [17].

From an engineering point of view, it appears to be more logical to define the fatigue limit or endurance limit as the highest stress amplitude for which failure does not occur after high numbers of load cycles. This definition should cover situations where fatigue failures are unacceptable e.g. in various cases of machinery. Design stress levels must then remain below this limit as a material property [18].

Table (6) low to high and high to low stress program results at 250°C.

Alloys	Specimen number	Type of loading Mpa)(	Number of cycles N_{fc} *1000	Number of cycles N_{fc} when D_{fc}=1 *1000
5086	39	100-150	18	35.6
5086	19	100-150	19	35.6
5086	26	100-150	17	35.6
5086	8	150-100	10	35.6
5086	32	150-100	14	35.6
5086	5	150-100	11	35.6
6061	17	100-150	34	67
6061	6	100-150	64	67
6061	1	100-150	82	67
6061	39	150-100	50	67
6061	20	150-100	34	67
6061	18	150-100	42	67

Table (7) Creep, fatigue, total and Miner cumulative damage.

Metals	Creep damage D_c	Fatigue damage D_f	Experimental total Damage D_{fc}	D Miner
5086	0.0532	0.4524	0.505	1
	0.05617	0.477566	0.5337	1
	0.05026	0.4273	0.47754	1
	0.029563	0.25135	0.281	1
	0.041388	0.35189	0.393	1
	0.03252	0.2765	0.309	1
6061-T651	0.00836	0.499879	0.5078	1
	0.015754	0.94095	0.9558	1
	0.020185	1.2056	1.22467	1
	0.012307	0.73512	0.7467	1
	0.00836	0.499879	0.5078	1
	0.01034	0.6175	0.6273	1

Costa and Silva [19] proposed a temperature factor (K_T) that is able to properly incorporate the nin-conventional behavior (fatigue limits) of some materials. It will also be shown that the new proposed temperature factor may be applied also to conventional materials with improved accuracy being than a more universal temperature factor.

The fatigue-creep tests were carried out at stress ratio R=-1 and at 250 ° C. Based on the fatigue and on the creep master curves, fig. (5) and fig. (6) or the relationships equations. Miners rule [20] is an example of a simply way to account for damage accumulation due to different fatigue cycles. This damage fraction rule is also designated by linear cumulative damage law (LCD).

It was explained with experimental results that the fatigue of the testing material decrease with increasing temperature. From the stress point of view, the effect of temperature is observed in a different manner. The fatigue strength and fatigue life of testing material decreases with increasing temperature (figure (4)). This finding s are in good agreements with concluded remarks of Ref.(7,14,19).

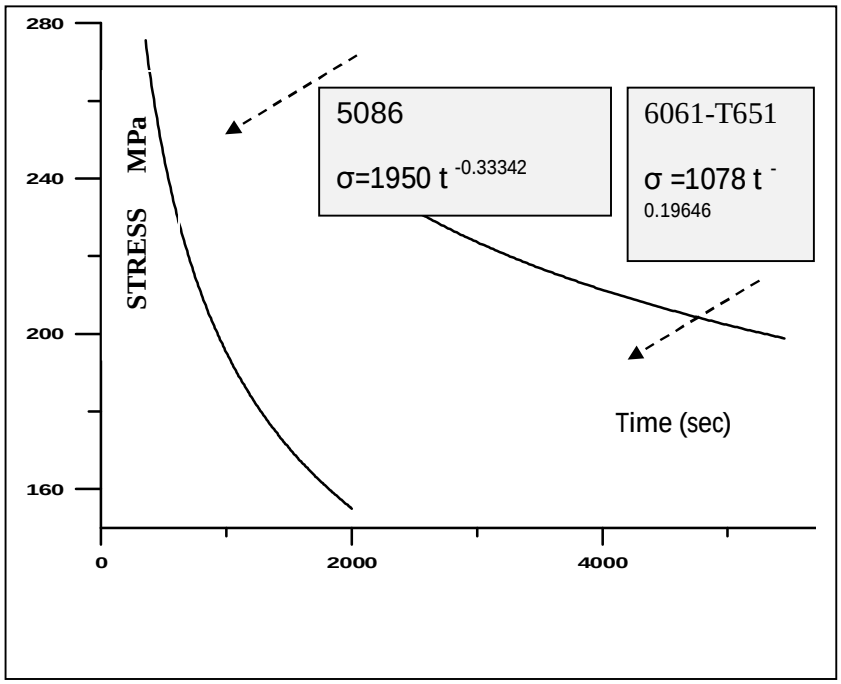


Figure (6); Creep test for 5086 and 6061-T651Al. Alloys.

For the fatigue it states that failure occurs when the following condition is verified, the fatigue damage is,

$$\sum_{1}^{N} \frac{n_i}{Nfi} = 1 \quad \ldots\ldots(2)$$

Where N_f is the number of cycles to failure at stress level σi and ni is the number of cycles applied at each stress level Бi of the fatigue cycle. The above formula provides a failure criterion for fatigue. The creep damage D_c condition is given by $\sum_{1}^{N} \frac{t_i}{t_{ci}} = 1 \quad \ldots\ldots(3)$

where t_{ci} is the creep rupture lifetime at stress level σ_i and t_i is the time applied at each stress level σ_i [21].

Latter Bowman and Barker [22] suggest a combination of both damage fraction rules to analyze experimental data

$$\sum_{1}^{N} \frac{n_i}{N_{fi}} + \frac{t_i}{t_{ci}} = 1 \quad \ldots\ldots(4)$$

For the present study the above equation is modified to take the form

$$\sum_{1}^{N} \frac{n_i}{N_{fi}} + \frac{t_i}{t_{ci}} = D_{fc} \quad \ldots\ldots(5)$$

D_{fc} is the fatigue-creep interaction damage which can be determined experimentally.

It is clear that figure (4), the weakest metal is 5086 Al. alloy because the endurance limit is lower value compared with the other metal.

Several creep-fatigue damage laws have been proposed. The linear damage rule was selected for employing in this investigation because it has been long used in the practical design code [23] from its simplicity and easiness to apply in variable loading.

Fig. (7) illustrate the creep-fatigue damage diagram calculated by equation(2) and (3). The bold line in the fig. shows the line $D_f + D_c = 1$ (LDR) and the experimental data located around the $D_f + D_c = 0.5$

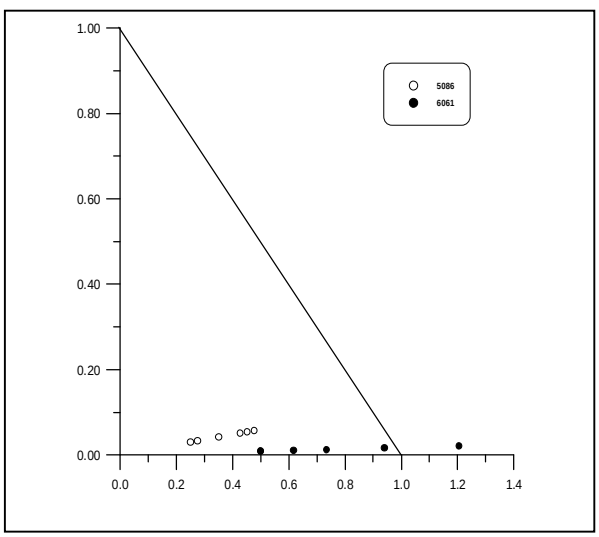


Figure (7); Fatigue-creep damage diagram by linear damage rule

Figure(7) illustrate the creep-fatigue damage diagram calculated by equation (2) and (3). Most of the experimental data denoted with open and solid circles located around the $D_f + D_c = 0.5$. Zhang and Sakane [24] found that the damage due to fatigue and creep located around $D_f + D_c = 0.6$ for type 304 stainless steel with the actual results.

Figure (8-A) shows a comparison between the lives estimated by (LDR) and the actual lives for 5086 Al. alloy. The linear damage rule estimated the fatigue-creep lives mostly within a factor more than two i-e LDR showed overestimated predictions. These results are in good agreement with findings of Ref. [24].

Figure (8-B) compares the experimental fatigue-creep lifetime and LDR predictions for 6061-T651 Al. alloy. Also the LDR predictions are overestimated but less than the predictions of 5086 Al. alloy. These results are agreed with the results of Ref. [25].

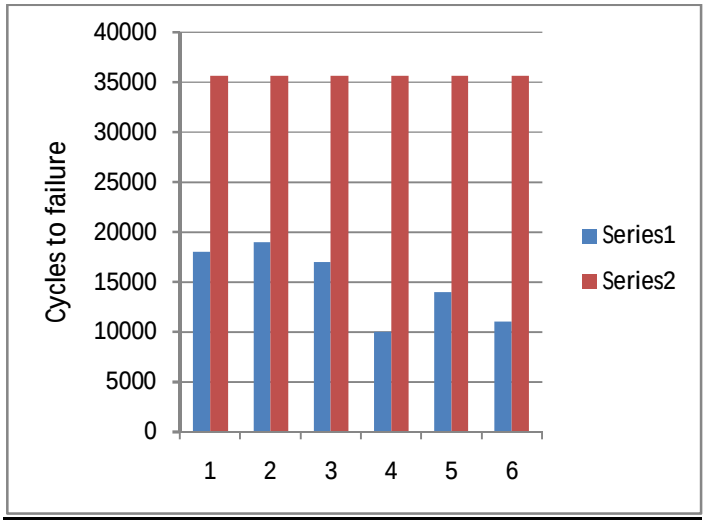


Figure (8-A); A comparison between experimental results(series 1) and Miner prediction(series 2) of cycles to failure in fatigue-creep interaction for 5086 Al. **alloy**

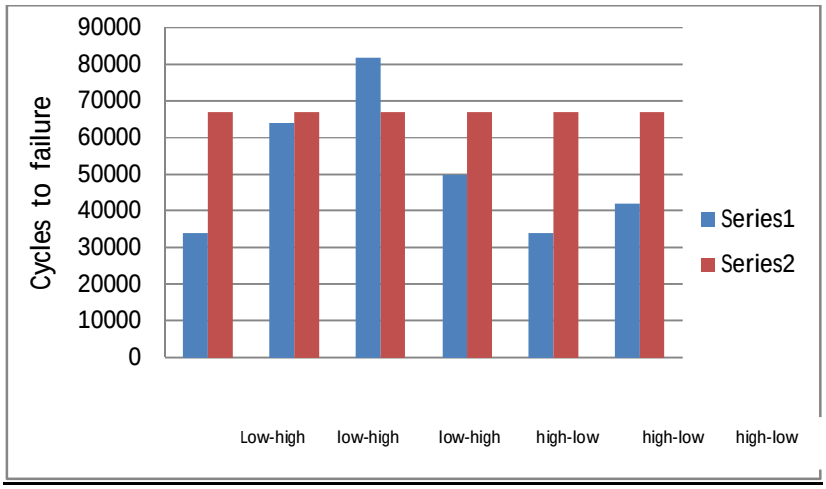


Figure (8-B); A comparison between experimental results (series 1) and Miner prediction (series 2) of cycles to failure in fatigue-creep interaction for 6061-T651 Al. alloy

CONCLUSIONS

Fatigue strength, life cumulative damage and endurance fatigue limits of 5086 and 6061-T651 aluminum alloys were investigated. The following conclusions could be derived from this investigation:-

1- For both alloys, fatigue endurance limit reduced at 250 ° C compared with that at room temperature.
2- Fatigue-creep testing of 5086 and 6061-T651 aluminum alloys were performed at stress controlled, and stress reversed loading ratio R=-1 .
3- The creep and fatigue damage was evaluated based on the linear damage rule (LDR). The experimental damage summation due to fatigue and creep may be taken the form :- $D_f + D_c = 0.5$
4- The fatigue-creep lifetime predictions due to LDR were overestimated compared with the actual lives.

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