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Fatigue Life Prediction at Elevated Temperature under Low – High and High – Low Loading Based on Mechanical Properties Damage Model

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ABSTRACT

In this work, an experimental study was carried to obtain the fatigue accumulation damage for aluminum alloy, 2024-T4 under rotating bending loading and stress ratio R= -1. The experiments were done at RT(room temperature) ,25^{o}C ,and 200^{o}C. A modified damage stress model was suggested to predict the fatigue life under elevated temperature which has been formulated to take into account the damage at different load levels. The present model results were compared with the experimental results and those calculated by the most fatigue damage model used in fatigue (Miners rule). The comparison showed that the present model presents reasonable factor of safety while Miner model sometimes gave a factor of safety close to unity.

Keywords: Damage stress model, life prediction of elevated temperature, Miner rule.

تخمين العمرالكلالي عند درجة حرارية مرتفعة تحت تحميل منخفض-عالي و عالي- منخفض بالأستناد على نموذج الضرر للخصائص الميكانيكية

الخلاصة

تم في هذا العمل اجراء دراسة عملية للحصول على قيم كلل الضرر التراكمي لسبيكة من الالمنيوم من نوع (2024-T4) ، وتحت تحميل اللي الدوراني و عند معدل اجهاد (R= -1) .
لقد اجريت الاختبارات عند درجة حرارة الغرفة (RT 25^{o}C) و عند درجة حرارة (200^{o}C) .
تم اقتراح نموذج متطورلاحتساب معدل الاجهاد وذلك لتخمين عمر الكلال عند درجة حرارة عالية لاحتساب الضرر ، وتحت تأثير مستويات تحميل مختلفة .
لقد تمت مقارنة نتائج هذا النموذج الجديد المقترح ، مع نتائج الاختبارات العملية وكذلك مع أكثر النماذج اعتمادا في الحسابات الكلالية ، ألا وهي (Miner rule) .
لقد بينت المقارنة هذه ، بأن النموذج الحالي يمنح معامل أمان معقول ، بينما كان معامل الآمان الذي يعطيه نموذج (Miner) ،ذو قيم تقترب من الاحادية في بعض الاحيان .

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INTRODUCTION

In recent years, there has been an increasing trend in the automotive industry to use 2024 aluminum alloy. The mechanical and physical properties of aluminum alloys such as 2024 and 6063 made them attractive for use in cost-effective, light weight engineering components. Kowfie and Chandler [1], proposed a stress-based fatigue model for correlating data and predicting fatigue life under loading conditions where cyclic creep occurs. This model is an extension of the Basquin stress-life relation .The model is tested on published creep-fatigue data of copper, steels, β-Ti alloy and agreement is found to be very good.

Lee et al [2], used linear damage summation rule for welded joints. The results gave reasonable life predictions.

Dunne and Hayhurst [3], extended the continuum damage mechanics approach in order to predict the life of high-temperature components. This approach showed good prediction of fatigue life compared with the experimental ones.

Fatigue at elevated temperature is a damage process of the structural components produced by cyclic thermal loads. Under these loads a component can suffer unacceptable geometric deformation and change in its material properties. Cracks may appear in the component as a sequence of constraint and cyclic thermal loads [4].

However, in order to successfully use such an alloy in components intended for long life applications it is necessary to understand its behavior under fatigue and thermal fatigue. The effect of different loading at high temperature on fatigue behavior of 2024 T4 aluminum alloy was investigated. In this paper, a stress – based approach to correlating data and predicting the fatigue life under fatigue-creep interaction is presented.

A proposed model was designed and applied to the experimental results. The life predictions obtained from the proposed model and Miner rule with predictions were also presented in this paper.

THEORETICAL CONDITIONS

All the fatigue S-N curves of the metal (2024Al alloys) under RT and elevated temperatures can be analyzed based on Basquin equation form as follows: [5].

$$\sigma_f = A N_f^{\alpha} \quad \text{.... (1)}$$

Where σ_f is the applied stress at failure

N_f is the number of cycles at failure due to the applied stress σ_f

A and α are material constants that can be evaluated by linearizing the curve by re-writing equation (1) in logarithmic form as follows:

$$\alpha = \frac{h\sum_{i=1}^{h}\log\sigma_f \log N_f - \sum_{i=1}^{h}\log\sigma_f \sum_{i}^{h}\log N_f}{h\sum_{i=1}^{h}(\log N_f)^2 - [\sum_{i=1}^{h}\log N_f]^2} \quad \text{... (2)}$$

And

$$\log A = \frac{\sum_i^h \log \sigma_f - \alpha \sum_{i=1}^h \log N_f}{h} \quad \text{...... (3)}$$

Where (i) is the number of readings or (i= 1, 2, 3 ….. h)
And (h) is the total number of readings

EXPERIMENTAL WORK

Material

The material is 2024-T_4 alloy, which is an aluminum copper alloy of widely industrial use such as airplanes, turbine blades and aerospace industries [7]. This alloy has good mechanical properties such as mechanical strength, light in weight and high in corrosion strength [2]. The character (T) represents thermally treated to produce stable tempers other than as fabricated alloy. The digit (4) represents how the alloy has been fabricated and it always followed by the symbol (T) [14].

CHEMICAL COMPOSITION

Chemical composition of the alloy was analysis at (the specialized institute for engineering industries Baghdad-Iraq), using x-rays method. The results obtained, are compared with the American standards, and tabulated as shown in table (1).

Table (1) Experimental and standard chemical composition of 2024-T_4 Al. alloy, wt%

Material	**Cu**	**Mn**	**Mg**	**Zn**	**Si**	**Fe**	**Ni**	**Al**
2024-T_4 experimental	4.21	0.48	1.33	0.28	0.38	0.41	0.09	Rem.
2024-T_4 standard	4.4	0.6	1.5	0.25	0.5	0.5	-	Rem.

MECHANICAL PROPERTIES

Tensile tests were carried out at RT(room temperature, 25^{o}C) and at elevated temperature (200^{o}C) in order to be used in the analysis of the cumulative fatigue-creep interaction.The tensile tests was done using (Instron 225) testing machine which has a maximum capacity of 150KN. For creep and fatigue-creep tests, a small furnace was design and built to raise the temperature of the specimen to a known elevated temperature (200^{o}C). Thus, an electrical furnace was made with suitable dimensions of (80*90*120 mm). The furnace can be attached to the testing machine, with a thermal control board as shown in Fig. (1)a. More details of the tensile testing at RT 25^{o}C and 200^{o}C can be found elsewhere [7].The mechanical properties of the alloy used can be illustrated in table (2).

Table (2) Mechanical properties of 2024 Al alloy

Condition of Property	σ_u(MPa)	σ_y(MPa)	E(GPa)	Ductility %	Hardness (HB)
Room Temp.(25^{o}C)	515	361	77	19	121
Standard	472	325	73	20	120
200^{o}C	332	207	52	23	89

FATIGUE TESTING MACHINE

Rotating bending fatigue tests were conducted at Room Temperature (25^{o}C)and 200^{o}C under stress ratio R=-1. This machine was used for creep, fatigue and fatigue-creep interaction tests. The test rig has a property of automatic cut-off when specimen fails. Fig. (2) a. Shows the fatigue-creep testing machine, which used in the ordinary tests at RT (25^{o}C). While Fig. (2) b. shows the fatigue-creep testing machine, with designed furnace for testing specimens at 200^{o}C.

Figure (2a) the fatigue-creep testing machine

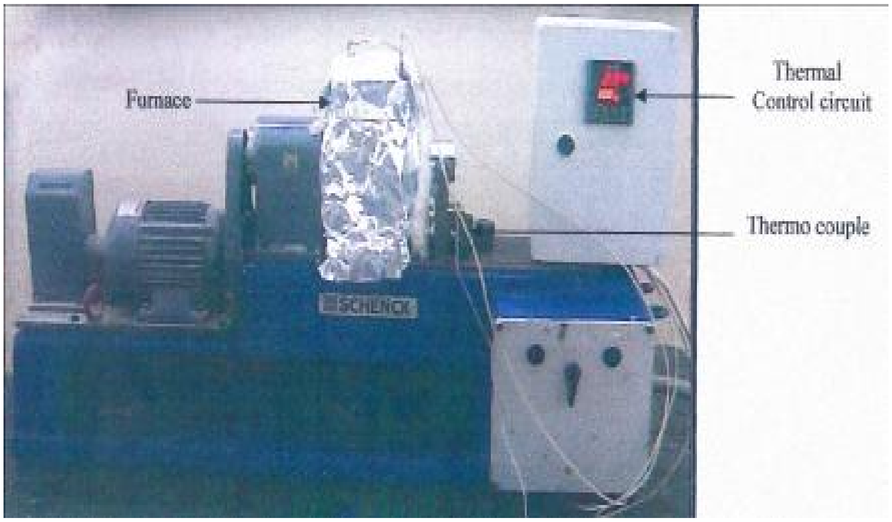

Figure (2 b) the fatigue-creep testing machine with furnace

FATIGUE-CREEP INTERACTION SPECIMEN

Fig. (2c) shows the shape and dimensions of fatigue-creep specimen. The manufactured specimens were classified into three groups as given in table (3).

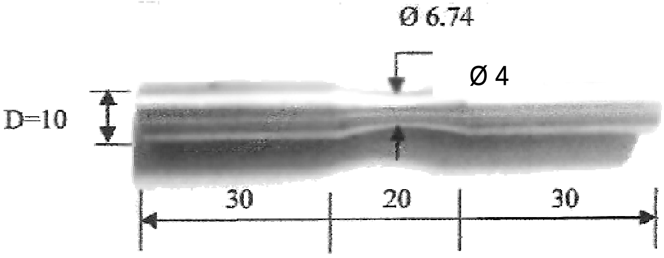

Figure (2 c) the shape and dimensions of fatigue-creep Specimen (All dimensions in mm)

Table (3) the plan of the experimental work

S-N curve fatigue tests	**12 specimens**
S-N curve fatigue-creep tests at 200°C	12 specimens
Cumulative fatigue-creep tests at 200°C	10 specimens

The average roughness (Ra) for all the specimens were in the range of (0.1 to 0.5) µm [5].

EXPERIMENTAL RESULTS

S-N curve fatigue tests

Table (4) gives the results of 12 specimens subjected to applied load (F) and the bending moment (M) which can be calculated from

$$M = F * L \qquad \text{… (4)}$$

Where M in N.mm

L is the moment arm = 160 mm

The bending stress σ_b can be calculated from

$$s_b = \frac{My}{I} \qquad \text{… (5)}$$

Where y is the distance from the tip to the neutral axis of the mini-diameter of the specimen d, $r = \frac{d}{2}$ and d = 4 mm, $I = \frac{\pi d^4}{64}$ which is the second moment of inertia of the specimen. Thus, the bending stress (σ_b) was calculated from equation (6).

$$s_b = 25.465 F \qquad \text{… (6)}$$

Table (4) S-N curve fatigue test results

Specimen No.	N_f cycles	Applied bending stress σ_b(MPa)	Average N_f cycles
1,2,3	**16800, 19600, 20900**	**350**	**19100**
4,5,6	**305100, 288600, 266900**	**250**	**286867**
7,8,9	**1628251, 1086672, 1886625**	**225**	**1533178**
10,11,12	**4855682, 4226871, 4356525**	**200**	**4479693**

The application of equation (2) and (3) using the data of table (4), average data, can be seen in equations below and listed in table (5):

Where

$$\alpha = \frac{4*53.824-9.594*22.574}{4*130.595\ \ 509.505} = \frac{-1.278}{12.795} = -0.0999 \cong -0.1$$

And

$$\log A = \frac{9.594+0.1*22.574}{4} = 2.950$$

A= 892

Table (5) shows the parameters of equations above

Log σ	Log Nf	Log σ lof N_f
2.544	4.281	10.890
2.397	5.457	13.082
2.352	6.185	14.548
2.301	6.651	15.304
Σ = 9.594	Σ = 22.574	Σ = 53.824

So equation (1) become

$\sigma_f = 892\ N_f^{-0.1}$

The behavior of 2024- T4 under constant fatigue stress amplitude and at RT (25°C)can be illustrated in Fig.(3).

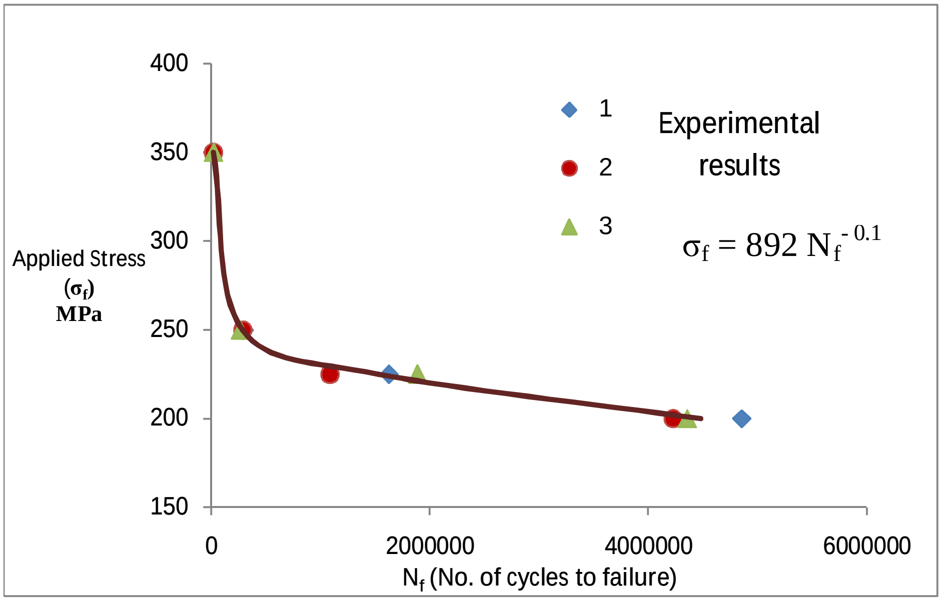

Figure (3) The S-N curve behavior under RT (25°C) condition.

S-N curve fatigue tests at 200°C

The same applied stresses were considered and the results are shown in table (6).

Table (6) Experimental fatigue S-N curve results at 200°C

Specimen No.	Life N_f cycles	Applied bending stress (MPa)	Average life
13,14,15	8800, 10600, 9000	350	9467
16, 17, 18	105600, 122800, 131500	250	119967
19,20,21	480600, 390800, 405600	225	425467
22,23,24	1200800, 1146000, 980800	200	1109200

The same procedure was used in calculating the material constants (A, α) as mentioned before and the results can be shown in Fig.(4).

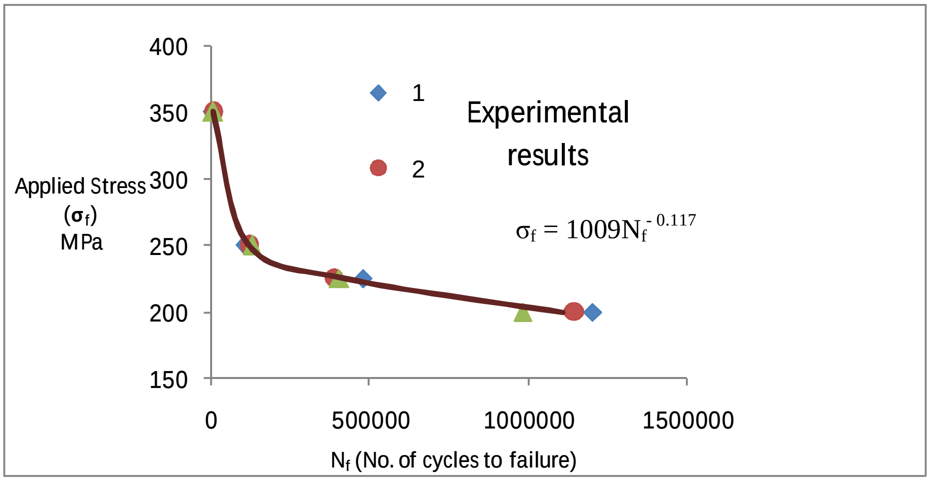

Figure (4) The fatigue behavior of 2024-T_4 at 200°C

Cumulative fatigue damage at 200°C

The third group of specimens was tested under variable loadings i.e. low to high (L-H) (200 - 300 MPa) and high to low (H-L) (300 – 200) MPa. Each program represents $2x10^4$ cycles divided equally on the two applied stresses as shown in fig. (5).

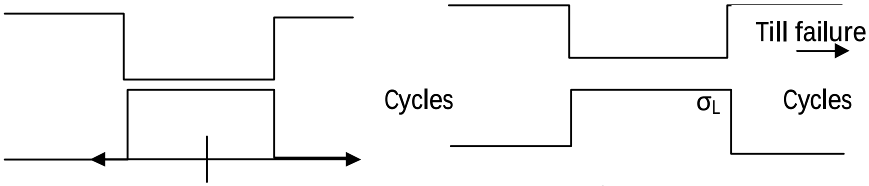

Figure (5) L-H and H-L fatigue tests at 200°C

Table (6) shows the experimental results obtained for the third group.

Table (6) Variable amplitude test results at 200°C

Specimen No.	**Low-high (fatigue life cycles)**
25, 26, 27, 28, 29	81600, 102800, 117600, 132800, 114900
Specimen No.	High-low (fatigue life cycles)
30, 31, 32, 33, 34	65600, 58900, 70100, 74100, 52100

DISCUSSION

S-N curves (original and 200°C fatigue)

As shown in Fig. (6) the original material at RT(room temperature, 25°C) and at 200°C fatigue tests results. A comparison between these results is also shown in the figure and the reduction in the fatigue endurance limit of the experimental section material can be noticed. The reduction percentage at 200°C was (15 %) in comparison with the original specimen, is a result of over aging of the precipitation hardened material structure [8].

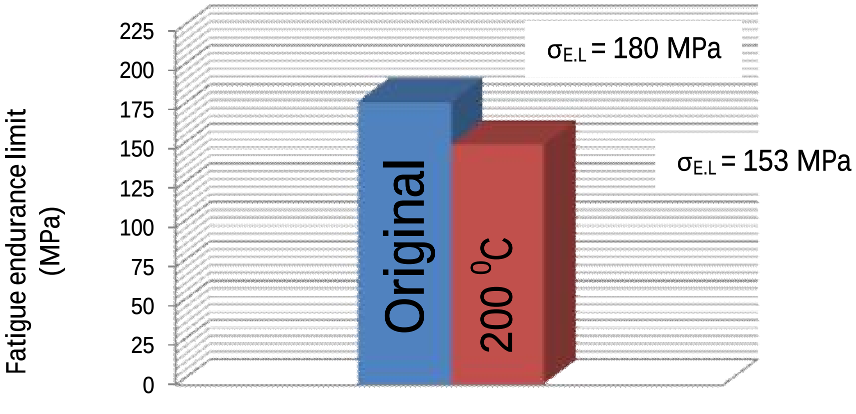

Figure (6) Comparison of the fatigue endurance limit (at 10^7 cycles)

Mahir [7] tested the same material at 150 °C and obtained the fatigue endurance limit $\sigma_{E.L}$ = 150 MPa at 10^7 cycles while in the present work the $\sigma_{E.L}$ was 153 (MPa) at 200°C.

In order to predict the residual life of a material. It is important to formulate a method to evaluate the fatigue damage accumulation. For many years, design engineers used Palmgren – Miner law, linear damage rule (LDR) and its modification to predict fatigue life of components in the case of variable loading [9].Recently, a new approach, based on damage mechanics, has been proposed [6, 7, 8].

PROPOSED MODEL

Aid [13] proposed a damage stress model (DSM) based on the S-N curve which takes the form:

$$D_i = \frac{\sigma_{equ.} - \sigma_{i+1}}{\sigma_u - \sigma_{i+1}} \qquad \ldots (10)$$

Where σequ. is the equivalent stress of damage at the level i+1, σ_{i+1} stress at the level i+1and σ_u is the ultimate tensile stress.

In the present study a modified (DSM) model is proposed based on the slope of the S-N curve. This model may take the form:

$$D = \left(\frac{\sigma_u - \sigma_H}{\sigma_y - \sigma_L}\right) s - Ncurvestop \quad e \qquad \ldots (11)$$

The above model was applied to fatigue life at different conditions of working and σ_u, σ_y are the material properties at that given conditions, i.e at 200°C.

The number of programs (X) and the cumulative fatigue damage parameters (D) for three cases of prediction is given in table (7).

Table (7) the main parameters which evaluate the fatigue cumulative damage

Parameters	Experimental	Miner – rule	Present model
X	**L – H** **4.08, 5.14, 5.88, 6.64, 5.745**	**3.083** **Constant**	**2.58** **Constant**
	H – L **3.28, 2.945, 3.505, 3.705, 2.605**		
D **200°C**	**L – H** **1.323, 1.666, 1.906, 2.153, 1.863**	**1, 1, 1, 1, 1**	**0.837** **Constant**
	H – L **1.063, 0.957, 1.136, 1.201, 0.844**		

CONCLUSIONS

1- The behavior of 2024-T4 aluminum alloy was studied under RT (room temperature, 25°C) and thermal fatigue using rotating bending loading with stress ratio R = -1.For allowing symmetric strain amplitudes (R=-1) within the cyclic loading experiments, without affecting adversely the mechanical behavior of the specimen.

2- A modified damage model based on the S-N curve and mechanical properties taking into account the effect of load history was introduced in this study.

3- The proposed model correctly follows the experimental results with large safety factor while Miner rule gave safety factor close to unity for specimens subjected to high – low stresses.

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