Effect of Hold Time Periods at High Temperature on Fatigue Life In Aluminum Alloy 2024 T4

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Abstract

In some applications, the aluminum alloy 2024 T4 may be subjected to an interaction of fatigue and creep effects at high temperature. This paper investigates the effect of this interaction by studying the effect of constant amplitude fatigue (CAF) and creep separately, and then fatigue-creep interaction is introduced by testing the alloy under constant amplitude with some holding time periods through the test at high temperature (150 ^{o}C). The results showed that the life time of the alloy decreases due to fatigue-creep interaction as compared to creep alone in about 77%, and in about 80% as compared with fatigue alone. This is a result of accumulated fatigue damage superimposed on creep damage. Creep allows more free spaces for fatigue cracks paths that accelerate failure. A theoretical model to calculate the time to failure due to fatigue-creep interaction has been proposed. This theoretical interaction model predicts very close time to failure values to the experimental results.

Keywords: fatigue-creep interaction, aluminum alloy 2024 T4, constant amplitude interaction,

تأثير فترات المسك عند درجة حرارة عالية على عمر الكلال لسبيكة ألمنيوم 2024 T4

الخلاصة

في بعض التطبيقات قد تتعرض سبيكة الالمنيوم المصنفة (2024 T4) الى تداخل بين تاثير الكلال و الزحف في درجات الحرارة العالية. يدرس هذا البحث تاثير هذا التداخل من خلال دراسة تاثير الكلال ثابت السعة و تاثير الزحف على السبيكة بشكل منفصل, ثم دراسة تداخل تاثير الزحف و الكلال من خلال فحص السبيكة تحت الكلال ثابت السعة مع اعطاء فترات توقف زمنية خلال الفحص في درجات الحرارة العالية (150 ^{o}C).بينت النتائج ان عمر السبيكة ينخفض نتيجة تداخل الكلال مع الزحف مقارنة مع عمر الزحف لوحده بحوالي 77%و و عن عمر الكلال وحده بحوالي 80%, نتيجة تراكم ضرر الزحف مع ضرر الكلال، حيث يؤدي الزحف الى زيادة المسافات البينية امام مسارات الشقوق المتولدة من الكلال مما يعجل حدوث الفشل. تمّ اقتراح نموذج نظري لحساب الزمن للفشل نتيجة تداخل تأثير الكلال والزحف واستطاع هذا النموذج التنبؤ بنجاح بقيم أزمان للفشل مقربة جدا" للنتائج العملية.

الكلمات المفتاحية: تداخل الزحف –الكلال, سبيكة المنيوم (2024 T4), تداخل ثابت السعة.

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List of Symbols

English Symbols		
Symbol	**Description**	**Units**
A	Constant	
B	Constant	
D	Damage	
D_{exp}	Experimental damage for constant amplitude fatigue-creep interaction.	
D_p	Fatigue damage due to variable amplitude fatigue-creep interaction.	
E	Modulus of elasticity of the material	MPa
h	Total number of readings	
HB	Brinell hardness	
i	Number of reading	
n	Number of cycles of stress σ applied to a specimen	cycles
N_{ff}	Number of cycles to failure due to constant amplitude fatigue.	cycles
R	Stress ratio	
S	Stress, in S-N curve	MPa
s	Total number of hold time increments.	
t	Time	hour
$t_{f,the}$	Total theoretical time to failure.	hour
t_{fc}	Total time to failure by creep only.	hour
$(t_{fc})_{\sigma i}$	Time to failure due to creep only at the applied stress σ_i	hour
t_{ff}	Total time to failure by constant amplitude fatigue only.	hour
t_h	Holding time period.	hour
t_r	Rotation time in constant amplitude fatigue-creep interaction.	hours
W	Creep damage due to constant amplitude fatigue-creep interaction.	
w	Applied load by fatigue testing machine.	N
x	Number of rotating program repeats for constant amplitude fatigue-creep interaction.	
y	Number of holding time periods repeats for constant amplitude fatigue-creep interaction.	

GREEK SYMBOLS		
δ	Cantilever specimen deflection	mm
ε	Strain	
ε^o	Creep strain rate.	
ε^o_{ss}	Steady-state strain rate	1/hour
ε_f	Failure strain.	

$(\varepsilon_f)_{\sigma i}$	Failure strain due to creep only at the applied stress σ_i	
ε_i	Initial strain	
σ_u	Ultimate tensile strength.	MPa
σ_y	Yield stress.	MPa
ω	Number of revolutions per minute of the rotating motor of the fatigue testing machine.	RPM
α	Constant	

Introduction

Failures of most engineering components operating at elevated temperature under cyclic loading are caused by a complex process, including not only fatigue, but also creep and the action of aggressive environments. These processes may act independently or interactively. Creep damage, which is a time-dependent process, depends primarily on the history of stress and temperature applied to the component; whereas fatigue damage is generated by the cyclic stress and depends primarily on time-independent plastic strain. When the two damage components act in a combined manner, a creep-fatigue interaction develops. Many attempts have been made in the last three decades to analyze the creep-fatigue interaction for life prediction of ferrous and non-ferrous materials.

B. Michel, and **C. Poette**[1] developed a specific approach for crack initiation assessment under creep-fatigue loading, in high temperature Fast Reactors components, based on fracture mechanics analysis, which was

Validated on experimental results for tabular specimens with internal axisymetric surface cracks. Metallurgical examinations on these specimens confirmed that the initiation assessment of the approach is conservative even for a different geometry than the CT specimen on which the method was set up. However, the conservative was reduced when the creep residual stress field was relaxed during the hold time**Bhoje** and **Chllapandi** [2] dealt with characteristic features of Fast Breeder Reactor (FBR) with reference to creep-fatigue design. For the analysis reported in their paper, material constitutive models developed based on ORNLB (Oak Ridge National Laboratory) and Chaboche viscoplastic theories were employed to demonstrate the potential of FBR components for higher plant temperatures and/or longer life. The results were presented for the studies carried out towards life prediction of Prototype Fast Breeder Reactor (PFBR) components.

Hussein et.al[3] were studied both static and dynamic (fatigue) mechanical properties for Al-alloy 2024, using the tensile tests for static mechanical properties and fatigue tests for dynamic mechanical properties under two conditions namely the room temperature and the 200-250 oC. This was to know the effect of the high temperatures on the behavior of the present alloy, which is widely used in varies applications. The conclusions that derived from this work were the dynamic mechanical properties reduced by a factor of 1.6 to 2.4 and the static mechanical properties reduced by a factor of 1.3 to 1.8.

In the present paper, the effect of creep-fatigue interaction in Al 2024-T4 alloy will be studied. This will be achieved by studying the effect of fatigue, then creep separately, and finally, creep-fatigue interaction.

Experimental Work

This investigation presents firstly the analysis of chemical composition and mechanical properties at room and elevated temperature of the selected material (Al 2024-T4 alloy), then testing its static mechanical properties at room and elevated temperatures and comparing the results. Secondly, preparing the creep and fatigue testing machine and cutting the specimens from a rod of the Al 2024-T4 alloy to a suitable size and number, then arranging a furnace of a suitable size, which can be attached to the testing machine with a thermal controlling system to control the required elevated temperature. Thirdly, testing some of the specimens in creep only, and another group in constant amplitude fatigue only at elevated temperature, then making an interaction between creep and fatigue on the rest specimens. Moreover, for each step of testing, a comparison of results is made with the other steps.

Material

The selected material for the experimental work is 2024-T4 aluminum alloy, which is an aluminum copper alloy of wide industrial use, mainly airplanes and aerospace industries, due to its desired mechanical properties such as light weight and high corrosion resistance [4].

The nominal and experimental chemical composition in percentage weight (%wt) of the selected material is shown in Table (1).

Two static tensile tests are performed, the first is at room temperature (approximately 30^{o}C), while the second is at elevated temperature (150^{o}C), which is the creep temperature of the alloy in this investigation [5].

The specimens are prepared for these tests according to the testing machine recommendations. Table (2) shows the tensile properties from the two tests with the standard values of the alloy at room temperature. Each value is an average of three tests.

Creep Test

Ten specimens were subjected to creep tests at different constant stresses after fixing a small furnace (up to 250^{o}C) on a creep tester. An extensometer was used for strain measurement. The furnace was heated to a temperature of (150^{o}C) as the creep temperature for Al 2024 T4 alloy [5].

The applied constant stresses at the creep temperature for the ten specimens were (300, 275, 260, 250, 225, 210, 200, 175, 160, and 150) MPa.

The specimen is considered as a cantilever beam due to type of loading in the testing machine as shown in Fig.(1), thus;

$$d_{yield} = \frac{T_{yield} L^3}{3E_{150^{o}C} I} \quad \text{..... (1)}$$

where, $\delta_{(yield)}$ is yield deflection, and it is determined experimentally;

$T_{(yield)}$ is the applied load at the yield stress, and it is equal to (10.5N);

L is the moment arm length as shown in Fig. (1), which is equal to (160mm)

E is the modulus of elasticity at (150 ^{o}C), and is equal to (62 GPa); and I is the second moment of inertia of the specimen, which is equal to (12.566mm^4).

So $\delta_{(yield)}$ is equal to (18.4mm), and from triangular similarity, the real deflection of the specimen is (1.15mm), so the total strain will be (0.0903) as determined by Eqn. (5)

The experimental results of creep tests are shown by (stress-time) diagram in Fig. (2). It can be easily noted that the time to failure increases with a decrease in the applied stress.

Constant Amplitude Fatigue Test

In this test, the furnace was heated to about (150 ^{o}C) after fixing it on a rotating bending fatigue tester. Twenty specimens of the alloy were subjected to the following stress amplitudes (300, 275, 260, 250, 225, 210, 200, 175, 160, and 150) MPa, two specimens were tested at each stress.

The recorded value of the number of cycles to failure was an average of two tests at the same stress amplitude.

Constant Amplitude Fatigue-Creep Test

The final test is an interaction test which contains both fatigue and creep effects. This test was achieved by rotating the specimen for n cycles at a stress and (150 ^{o}C), then holding it for a period of time t_h at same stress and temperature, then repeating the loading program until failure. The applied stresses at the creep temperature for twenty specimens were (300, 275, 260, 250, 225, 210, 200, 175, 160, and 150) MPa, two specimens were tested at each stress.

n represents the number of cycles required to initiate a crack. It has been suggest that n is approximately $0.9N_{ff}$ [6], but this value may be different at elevated temperature. Al-Amiri [7] has determined fatigue properties of Al 2024T4 at room and elevated temperature and obtained a factor that takes into account the decrease in life due to increasing test temperature. It can be predicted that the number of cycles required to initiate a crack (n) at (150 ^{o}C) is equal to 0.1 N_{ff} [7].

Holding time $(t_h)_i$ for **the applied stress (σ_i)** was determined approximately as the time required for 1% strain and considered constant for each holding period to make the time to failure reasonable under creep-fatigue interaction as follows;

$$(t_h)_i = \frac{0.01}{(e^{o})_i} \quad \text{……… (2)}$$

$$(t_r)_i = \frac{(n)_i}{60 \times w} \quad \text{………. (3)}$$

where: ω is motor speed of the testing machine which is equal to (2850)rpm;

Theory

In this article, theoretical relationships between creep and fatigue behaviors will be established to find the interaction effect theoretically which will be compared later with the experimental results.

Creep Calculations

There are three stages of creep. The overall creep behavior can be represented by the following equation [8]:

$$e = e_i + Bs^{m}t + ks^{g} \quad \text{….(4)}$$

The overall strain ε can be calculated by strain energy [9]:

$\varepsilon= (2T\delta)/\sigma$ …….. (5)

The initial strain ε_i in the first creep stage can be determined by [10]:

$$e_i = \frac{s}{E} \quad …….. (6)$$

The secondary region (II) is characterized by mean creep (creep strain rate, $e^{\cdot}_{\min} = e^{\cdot}$, is constant) in which competing mechanisms of strain hardening and recovery may be present. The mean strain rate can be calculated by [8]:

$$e^{\cdot} = Bs^m = \frac{de}{dt} \quad ……… (7)$$

B and m can be determined experimentally.

The third stage is the failure stage and there is no problem in discarding it.

By substituting Eqns. (5), (6), and (7) in Eqn. (4), the only unknown term is t_{fc} (time to failure) which can be easily determined.

Constant Amplitude Fatigue Calculation

The fatigue curve of a material is obtained by many constant amplitude fatigue tests, and can be presented by the following equation [11];

$$s = AN_{ff}^{\,a} \quad ……. (8)$$

A and a are constants that can be evaluated by linearizing the curve by putting Eqn.(8) in logarithmic form:

$$\log s = \log A + a \log N_{ff} \quad …… (9)$$

Using linear fitting and the least squares method, a and A can be determined.

$$a = \frac{\sum_{i=1}^{h} \log s_i \log N_{ff_i} - h\sum_{i=1}^{h} \log s_i \sum_{i=1}^{h} \log N_{ff_i}}{h\sum_{i=1}^{h} \left(\log N_{ff_i}\right)^2 - \left(\sum_{i=1}^{h} \log N_{ff_i}\right)^2} \quad ….(10)$$

$$\log A = \frac{\sum_{i=1}^{h} \log s_i - a\sum_{i=1}^{h} \log N_{ff_i}}{h} \quad ... (11)$$

Where i is the number of test, or (i=1, 2, 3,… h), and

h is total number of tests and it is equal to (10) in this case.

Constant Amplitude Fatigue-Creep Effect Calculation

In this case, two effects contribute to the life of the specimen, these are fatigue and creep. The interaction allows the use of Miner's rule for material fatigue life evaluation [12].

$$D = \sum \frac{n}{N_{ff}} \quad ……. (12)$$

By inserting creep effect as Robinson's time fraction damage rule [3], Eqn. (12) becomes:

$$\sum^{fatigue} \frac{n}{N_{ff}} + \sum^{creep} \frac{t_h}{t_{fc}} \le D \quad …. (13)$$

Eqn. (13) agrees the design criteria of Bhoje and Chllapandi [3], which assumed that the damage D is larger than the accumulated fatigue and creep damages as compared with Miner's rule.

By converting the fatigue damage part in Eqn. (13) to time damage, the equation becomes:

$$\frac{1}{t_{ff}} t_r x + \frac{1}{t_{fc}} t_h y = D \quad ….. (14)$$

$$t_{ff} = \frac{N_{ff}}{60 \times w} \quad …… (15)$$

Thus, the total time to failure t_f can be calculated theoretically as:

$$t_{f,the.} = t_r x + t_h y \quad …… (16)$$

In the present investigation, failure always occurred during the rotating part of the interaction program, thus;

$y \le x \le y+1$ …… (17)

where y is an integer.

Theoretically, and for safer design, let us assume that at failure the number of rotating programs is equal to the number of holding time period programs during any interaction test, i.e.

$x=y$ …… (18)

According to this assumption, the theoretically predicted failure time values should be less than the actual values. This is considered as a safe design.

Substituting Eqn. (18) into Eqn. (14) and re-arranging terms gives:

$y = D / [0.1+ (t_h/ t_{fc})]$ …… (19)

where $\frac{n}{N_{ff}} = \frac{t_r}{t_{ff}} = 0.1$ as stated previously in the experimental work.

Substituting Eqn. (18) again into Eqn. (16) gives:

$t_{f,the.} = y\,(t_r + t_h)$ …… (20)

Therefore,

$Father=D(t_r+t_{he})/[0.1+(t/t_{fc})]$ …(21)

The theoretical time to failure due to fatigue-creep interaction ($t_{f,the}$) can be predicted by Eqn. (21). The main parameters needed for such prediction are t_h, t_{fc}, and t_r at each stress amplitude. Besides, the damage value D is also needed. Trials of different values for D will be attempted to select the most appropriate value. The experimental damage D_{exp} at an applied stress σ_i can be calculated as follows:

$$D_{\exp} = \frac{nx}{(N_{ff})_{s_i}} + \frac{t_h y}{(t_{fc})_{s_i}} \quad ……. (22)$$

Results and Discussion

Three principal results will be outlined and discussed. These include the results of creep tests, constant amplitude fatigue tests, and the interaction tests.

Creep Results

The failure in this test is defined as the yield failure, [9] i.e. failure occurs when the deflection of the specimen reaches yield deflection. Table (3) shows all the creep statistics obtained from the experimental results and Fig. (3) shows the strain rate-stress relationship for the alloy. The last three readings were obtained by extrapolation to reduce the time of experimental work. Hence, the creep behavior of Al 2024-T4 can be expressed as:

$e^{o} = 9.332\times10^{-21} s^{\,6.876}$ ……… (23)

Constant Amplitude Fatigue Results

The constant amplitude fatigue behavior of Al 2024-T4 is shown in Fig. (4) and can be expressed as:

$s = 887.156 N_{ff}^{-0.1021}$ ……… (24)

It is predicted that the fatigue limit of Al 2024-T4 at 150 ^{o}C is (150 Mpa) at 3.5×10^{7} cycles.

Constant Amplitude Fatigue-Creep Interaction Results

The results of the tests are outlined in Table (4). The theoretical values of the time to failure due to fatigue-creep interaction (Eqn. (21)) have been calculated with three different D values, namely 1.0, 0.7 and 0.45. Table (5) shows the main parameters needed for such prediction; t_h, t_{fc}, and t_r at each stress amplitude. In addition, the experimental damage value (D_{exp}) is also listed.

Fig. (5) Compares the time to failure due to creep only, the theoretical values due to fatigue-creep interaction (Eqn. 21) and the experimental values under fatigue-creep interaction tests.

It is evident that the introduction of fatigue cycling to creep tests accelerates crack initiation and propagation and hence reduces the time to failure; i.e. promotes early failure [1]. The theoretical interaction model (Eqn. 21), with a *D*-value of 0.45, predicts almost identical time to failure values to the experimental results. The theoretical predictions can be used in safe design calculations.

Therefore, dependent on the degree of the required safety, the value of *D* is:

$0 < D \leq 0.45$ …… (25)

In fact, the value of the experimental damage (D_{exp}) at all the constant stress amplitudes used in this investigation was found to be in the range:

$0.430 \leq D_{exp} \leq 0.442$ …. (26)

With an average value of 0.435. Therefore, the use of Miner rule, which assumes a *D* value of unity [13], is unsafe since it predicts longer lives (*time to failure*) than the actual live.Fig. (6) shows the effect of the hold times at high temperature on the number of cycles to failure as compared to constant amplitude fatigue only. It is clear that hold times at high temperatures accelerate failure by allowing the crack, which is initiated by fatigue cycling for *n* cycles, to propagate through holding time period by increasing space distances between grains of the material microstructure [14]. The second fatigue cycling period and holding time period accelerates propagation of an already existing crack and the process continues until final failure occurs.

The experimental S-N curve from interaction tests can be described by the following equation;

$$s = 755 N_{ff}^{-0.1022} \quad \text{...... (27)}$$

This equation predicts lower lives and the fatigue limit is decreased to (128 MPa) at $3.5\text{x}10^7$ cycles due to the interaction. Fig. (7) shows the safe and unsafe zones for safer design (*D*=0.45) depending on theoretical damages values as compared with Miner's assumption.

Conculusions

The following conclusions can be drawn from this investigation concerning fatigue-creep interaction at 150 °C in the Aluminum alloy 2024-T4:

1. Hold times at high temperatures at a constant stress during a constant amplitude fatigue test reduces the number of cycles to failure.
2. There is a significant reduction in the time to failure during a fatigue-creep interaction test as compared to a pure creep test, especially at low applied stresses.
3. A theoretical interaction model has been proposed which predicts very close time to failure values to the experimental results.

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Table (1) Nominal and experimental chemical composition of Al 2024 alloy (%wt).

Element	Cu	Mn	Mg	Zn	Si	Fe	Ni	Al
Nominal Composition[4]	4.4	0.6	1.5	0.25	0.5	0.5	-	Rem.
Experimental Composition	4.1	0.45	1.3	0.3	0.2	0.3	0.1	Rem.

Table (2) Mechanical properties of Al 2024T4 alloy.

Property	s_y (MPa)	s_u (MPa)	Elongation%	E (GPa)	(HB)
Standard values [4](Room Temp.)	325	472	20	73	120
Experimental values (Room temp.)	352	502	16	80	118
Experimental values(150°C)	268	427	18	62	100

Table (3) Creep statistics of Al 2024 T4 alloy.

test	σ(Mpa)	t_{fc}(hour)	(ε_i)	ε^o (1/h)	(ε_f)
1	300	97.6	0.0048	8.25E-04	0.0854
2	275	145.2	0.0044	5.60E-04	0.0858
3	260	217.8	0.0042	3.75E-04	8.60E-02
4	250	286.4	0.004	2.87E-04	8.62E-02
5	225	605	0.0036	1.37E-04	8.65E-02
6	210	984	0.0034	8.47E-05	0.0868
7	200	1380	0.0032	6.07E-05	0.087
8	175	3540.2	0.0028	2.39E-05	0.0874
9	160	6654.2	0.0026	1.27E-05	0.0877
10	150	10495.4	0.0024	8.13E-06	0.0878

Table (4) Constant amplitude fatigue-creep statistics of Al 2024 T4 alloy

test	σ (Mpa)	N (cycles)	t_r (hours)	x	t_h (hours)	y	Total holding time (hours)	Total rotating cycles	Total rotating time (hours)	Experimental time to failure t_f(hours)
1	300	3633	0.021	2.083	11.415	2	22.83	7568	0.044	22.874
2	275	8982	0.052	2.044	16.92	2	33.84	18367	0.107	33.947
3	260	15683	0.091	2.04	25.316	2	50.632	32005	0.187	50.819
4	250	28403	0.166	2.01	33.222	2	66.444	56806	0.332	66.776
5	225	65496	0.383	2.045	69.93	2	139.86	133939	0.783	140.643
6	210	127299	0.744	2.08	113.25	2	226.5	265199	1.55	228.05
7	200	474398	2.774	2.04	158.478	2	316.956	968158	5.661	322.617
8	175	806333	4.715	2.01	404.858	2	809.716	1612665	9.43	819.146
9	160	1879805	10.993	2.08	763.358	2	1526.71	3916260	22.865	1549.618
10	150	2132725	12.477	2.04	1194.743	2	2389.48	4352500	25.453	2415

Table (5) Values of the main parameters for theoretical model predictions.

σ (MPa)	t_h (hour)	t_{fc} (hour)	$\frac{t_h}{t_{fc}}$	t_r (hour)	D_{exp}
300	11.415	97.6	0.117	0.021	0.442
275	16.92	145.2	0.116	0.052	0.437
260	25.316	217.8	0.116	0.091	0.436
250	33.222	286.4	0.115	0.166	0.433
225	69.93	605	0.115	0.383	0.436
210	113.25	984	0.115	0.744	0.438
200	158.478	1380	0.114	2.774	0.434
175	404.858	3540.2	0.114	4.715	0.430
160	763.358	6654.2	0.114	10.99	0.437
150	1194.743	10495.4	0.113	12.477	0.432

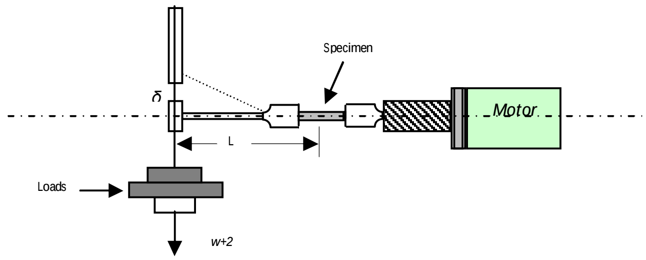

Figure (1) the Testing Machine

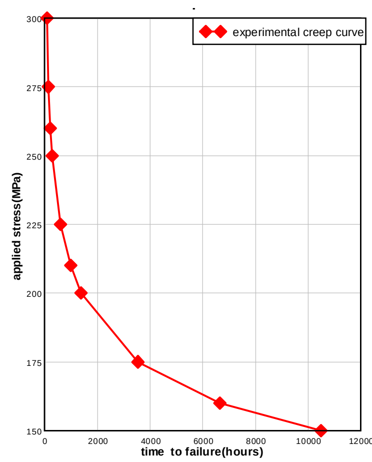

Figure (2) Experimental creep curve for Al 2024-T4 at 150 ^{o}C

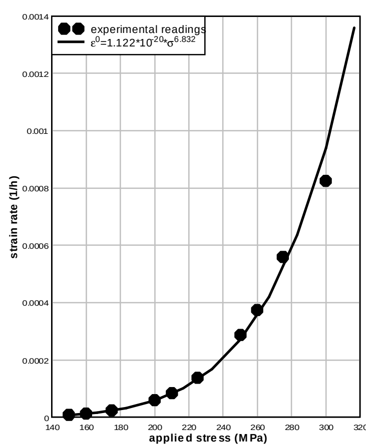

Figure (3) Strain rate-stress curve for Al 2024-T4 at 150 ^{o}C

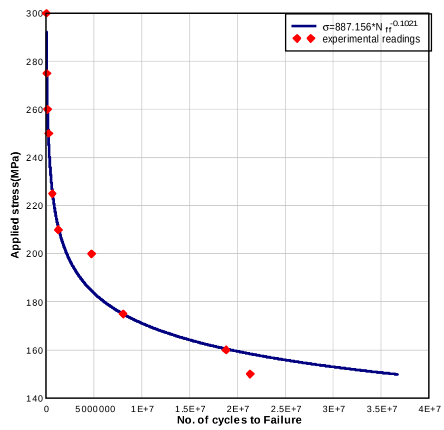

Figure (4) Constant amplitude fatigue curve for Al 2024-T4 at 150 ^{o}C

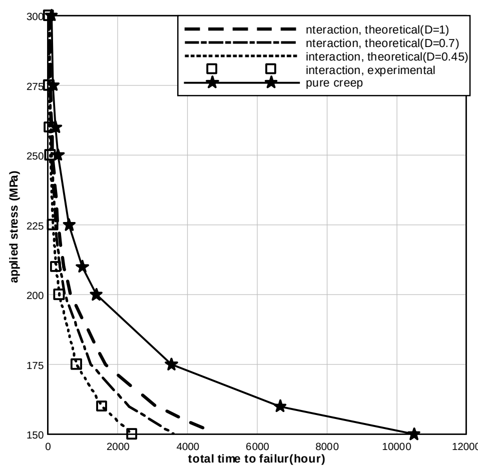

Figure (5) Comparison of times to failure due to creep only, Theoretical and experimental values due to fatigue-creep interaction

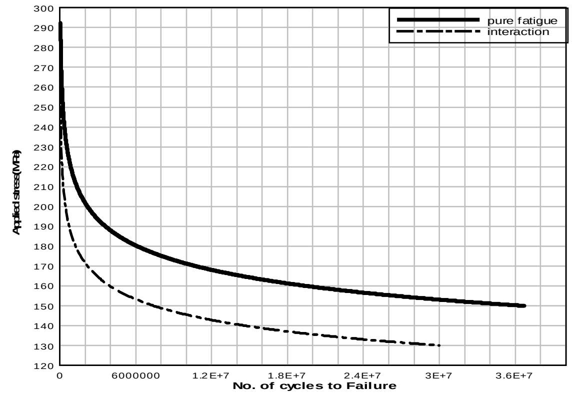

Figure (6) a comparison between fatigue life under constant amplitude And due to constant amplitude fatigue-creep interaction at 150^0C

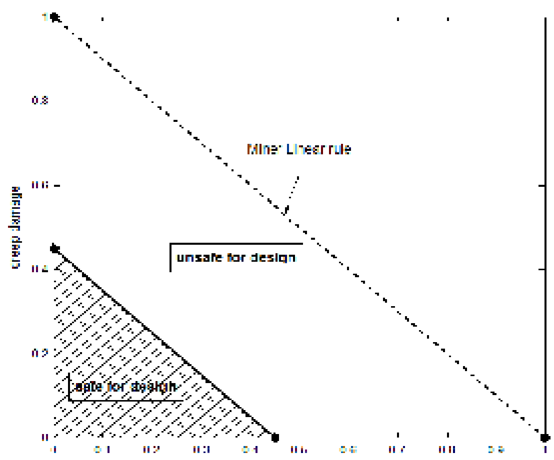

Figure (7) Constant amplitude fatigue-creep interaction diagram for Al 2024 T4 at 150 ^0C