Prediction of Fatigue-Creep Interaction Life of Aluminum Alloy AA7349 Using Electromechanical Devices

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ABSTRACT

In this present work, the behavior of AA7349 aluminum alloy under constant and cumulative creep-fatigue interaction has been studied by using an electrical system designed and built in order to investigate creep-fatigue interaction at different stress levels and temperatures. An hour glass shaped specimen of AA7349 aluminum alloy has been subjected to a constant and variable creep-fatigue tests performed under rotating bending loading and stress control at stress ratio R=-1.

The results of the creep –fatigue life have been studied by Miner rule and compared with the proposed and experimental methods. It was shown that the Miner rule and proposed model gave reasonable results and they are in a good agreement with the experimental fatigue lifetimes.

Keywords: Creep-fatigue interaction, 7349 Al-alloy, cumulative fatigue damage, proposed model.

تخمين عمر تداخل الكلال و الزحف لسبيكة الألمنيوم AA7349 بأستخدام أجهزة كهروميكانيكية

الخلاصة

تم دراسة سلوك سبيكة الالمنيوم AA7349 عند تداخل الزحف و الكلال الثابت و التراكمي بأستخدام منظومة كهربائية تم تصميمها و ذلك لتحقيق تداخل الزحف و الكلال عند مستويات أجهاد مختلفة و درجات حرارة مختلفة. و قد تعرضت عينة الالمنيوم AA7349 الى أختبارات تداخل الزحف و الكلال الثابت و المتغير تحت سيطرة الاجهاد و الانحناء الدوار بنسبة أجهاد R=-1.

تم دراسة نتائج تداخل الزحف و الكلال بأستخدام قاعدة ماينر و تم مقارنتها مع النموذج المقترح و الطريقة العملية. وقد تبين أن قانون ماينر والنموذج المقترح أعطت نتائج معقولة و كانت بتوافق جيد مع النتائج العملية.

الكلمات المرشدة: تداخل الزحف و الكلال, سبيكة الالمنيوم 7349, ضرر الكلال التراكمي, النموذج المقترح.

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INTRODUCTION

Components operating in power generation equipment such as power station, gas turbines or jet engine are exposed to the range of loading conditions during service. These include cycling stress or strain raised by thermo-mechanical cycling such as changing operating load or start up or shut down procedure of engine and the time dependent creep related with dwell time of on –load periods at high temperature. These components therefore have to be designed not only against the fatigue but also creep. In addition, the possible interaction between fatigue and creep must be considered [1].

Creep- fatigue failures are associated with temperature and time. They are associated with temperature because these phenomena are thermally activated from mid to elevated temperatures that are above about one third of the absolute melting temperature for metals. The time association arises because the temperature induces viscous effects depending explicitly upon time [2].

The interaction between creep and fatigue is proved to be an important factor in engineering safety design and it is a very complex and difficult problem for researchers in the relative fields [3].

Al-Alkawi, et al [4] 2010, many studies were investigations such as fatigue and creep test separately, and then fatigue-creep interaction of Aluminum alloy AA2024-T4 under constant amplitude and stress ratio of R=-1with some holding time periods at high temperature (150°C). They found that the lifetime 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 because of the accumulated fatigue damage superimposed on creep damage.

Al-Alkawi, et al [5] 2012 studied the behavior of 5086 and 6061-T651 aluminum alloys under the fatigue-creep interaction. The test was performed under control stress rotating bending at a stress ratio R=-1 and 250°C temperature. The results showed that the fatigue endurance limit for both alloys reduced at 250°C and the cumulative fatigue-creep interaction damage was found to be around 0.5 i.e. $D_F + D_c = 0.5$, Fatigue – creep interaction lives predicted by the linear damage rule which gave an overestimated prediction.

Zainab [6] 2012 evaluated the cumulative fatigue damage experimentally by testing specimens of aluminum alloy 2024-T4 under rotating bending loading and stress ratio R= -1 at room temperature 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.

Sa'ad [7] 2012 tested two aluminum alloys, 2024 and 5052 at stress ratio R=-1 and rotary bending loading to obtain the fatigue endurance limit for fatigue tests performed at room temperature, 100 °C, 200 °C and 300 °C then establish the S–N curve equations. It was found that the fatigue endurance limit had decreased with increasing the temperature and the reduction percentage in fatigue endurance limit for 5052 Al. alloy was higher than that of 2024 Al. alloy.

Holmström and Auerkari [8] 2013 developed a new model to predict the fatigue -creep interaction life of ferritic steel P91, austenitic steel 316FR, and Ni alloy A230 without the need to separate fatigue and creep damage or life fractions. The model depends on the creep rupture behavior of the material with a fatigue correction described by hold time (in tension) and total strain range at temperature**.**

Narasimhachary and Saxena [9] 2013 evaluated the creep–fatigue crack of 9Cr–1Mo steel under constant load amplitude conditions at 625^{o}C with various hold times. The crack growth data were observed using stress intensity factor range parameter (ΔK) and the time average value of time-dependent fracture mechanics parameter (Ct)avg. for the cycle-dependent crack growth and time-dependent crack growth rates, respectively. It was found that the crack growth rates per cycle increased with the increasing in hold time when crack growth data were plotted with the cyclic stress intensity factor, ΔK and the creep–fatigue interactions during crack growth are represented better by the (Ct)avg. parameter for various hold times implying that the P91 steel behaves in a creep ductile manner. The test results are also used for assessing E2760-10 for creep–fatigue testing.

Hao, et al [10] 2014 carried out an experimental study to obtain the creep–fatigue crack growth of nickel-based powder metallurgy superalloy FGH97 with 0 s and 90 s dwell time at different elevated temperatures .A new model is proposed containing a temperature parameter and accounting for creep–fatigue interactive effect for predicting creep–fatigue crack growth .The results showed that the proposed model has a good capability in correlating the crack growth rate and it was confirmed the validity of the model by available test results of Alloy 718 at 550 ℃ and 650 ℃ with various dwell times.

Cui and Wang [11] 2014 developed two estimation models to predict the fatigue -creep interaction life on high-chromium 10%Cr stainless rotor steel under complex loadings. Many experiments were carried out to determine model parameters, the prerequisite for the application and the limitations of each model. Two models are used to describe material deformation and damage in a different manner and both models show satisfactory results.

The current work aims to study the creep - fatigue interaction of aluminum alloy. This aim is required to design and built a control circuit in order to control the temperature inside the furnace and also design and built the furnace suitable with fatigue test rig available in the laboratory.

Creep-fatigue tests were carried out under constant and variable loading at different temperatures.

Experimental Work

The tested material was aluminum alloy (AA7349). This alloy is widely used in aircraft structural parts, aerospace applications and other highly stressed structural applications where very high strength is required. The alloy composition is given in Table (1), while the mechanical properties are given in Table (2).

Table (1) Chemical compositions of aluminum alloy (AA7349) wt.%

AA7349 (Standard) [12]	**Si**	**Fe**	**Cu**	**Mn**	**Mg**
	0.12	0.15	1.4-2.1	0.2	1.8-2.7
	Cr	**Zn**	**Ni**	**Ti**	**Al**
	0.1-0.222	7.5-8.7	0.05	0.05	-
AA7349 Experimental	**Si**	**Fe**	**Cu**	**Mn**	**Mg**
	0.12	0.15	1.4-2.1	0.2	1.8-2.7
	Cr	**Zn**	**Ni**	**Ti**	**Al**
	0.074	0.266	1.8	0.25	2.52

Table (2): mechanical properties of aluminum alloy (AA7349).

Property	**Yield stress, σ_y (MPa)**	**Ultimate Stress, σ_u(MPa)**	**Elongation %**	**Modulus of elasticity, E (GPa)**
Standard values [13]	410-570	480-620	-	-
Room temperature values	560	595	22	76

*The average of three readings is recorded in the above table

Specimen Preparation

Cylindrical hourglass specimens with minimum diameter of (6.74) mm were used in the fatigue-creep interaction test. All specimens were manufac tured according to DIN 50113 using CNC lathing Machine, The shape and dimensions of test specimen are shown in Figure (1).

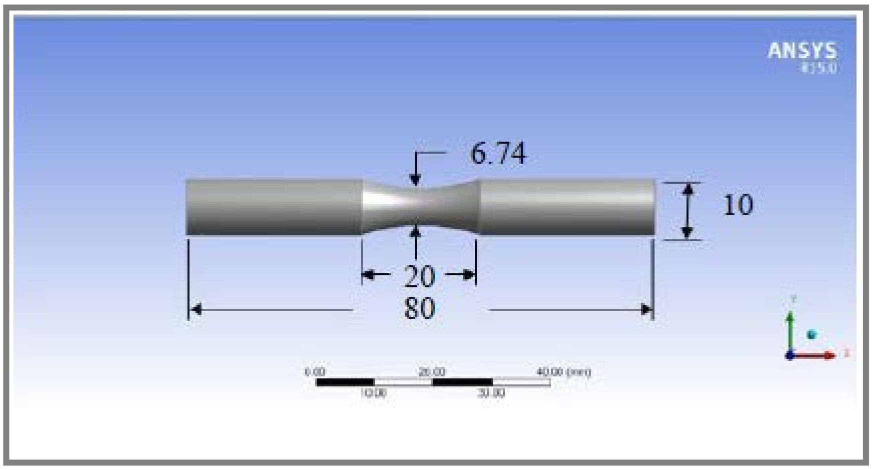


Figure (1): Fatigue test specimen dimensions in millimeter according to (DIN 50113) standard specification.

Roughness Test:
After machining the specimens, all the specimens were polished using the following steps:
1-The surface of the specimen is smoothed using different wet silicon carbide papers starting with (260) to (1200) µm for finishing.
2- The specimen is polished using diamond lapping compounds. The results of the surface roughness are given in Table (3):

Table (3): Surface roughness results of aluminum alloy (AA7349).

Specimen Number	**Average Roughness R_a (μm)**	**Peak Roughness R_t (μm)**
1	0.7	1.2
2	0.79	1.33
3	0.8	1.08
4	0.82	1.41
5	0.85	1.32
6	0.92	1.42
7	0.97	1.4
8	1.02	1.5
9	1.08	1.7
10	1.09	1.32

Fatigue Test

A fatigue–testing machine Schenck product of type PUN N rotating bending is used to execute all fatigue tests, with constant and variable amplitude. The fatigue specimen which is shown in Figure (1) has a round cross section and is subjected to an applied load form the right side of the perpendicular to the axis of specimen, developing a bending moment. Therefore the surface of the specimen is under tension and compression stress when it rotates. The value of the load (P) is measured by Newton (N), applied to the specimen for a known value of stress (σ) measured by (N/mm^2) and extracted from applying the relation below:

$$\sigma(N/mm^2) = \frac{32 \times 125.7 \times P(N)}{\pi \times d^3} \quad \ldots(1)$$

Where

the force arm is equal to 125.7mm, and d (mm) is the minimum diameter of the specimen [14].

For creep- fatigue interaction test a small furnace was attached to the fatigue testing machine with a digital thermal control unit board. An electrical heater of (2000W) was fixed inside the furnace with a K-type thermocouple to control the heating temperature inside the furnace [15]. The testing machine and peripheral equipments are shown in Figure (2).

Figure (2): PUN N rotary fatigue bending machine.

Electrical Control Circuit

A temperature controlled system is used to control the temperature inside the furnace and it is composed of essential elements which all affect its performance as shown in Figure (3). The electric control circuit is turned by miniature circuit breaker which provides overload and short circuit protection. The controlled variable, in this case, is the temperature which is measured by a thermocouple type K and converted to signal acceptable by the controller. The controller compares the temperature of the furnace measured by the sensor with the desired load temperature (the Set-Point) and actuates the final control device which is a contactor.

A contactor alters the manipulated variable (electricity) to change the quantity of heat being added or taken from the heater. The heater reaches a set point in about 95 Sec, 217 Sec at 100 ^{O}C and 200^{O}C, respectively. When power is connected to the coil of an on-delay timer, the time delay (t) begins. At the end of the time delay (t), the output is energized. Input voltage must be removed to reset the time delay relay and de-energize the output. The buzzer remains on for a small amount of time when the relay changes state.

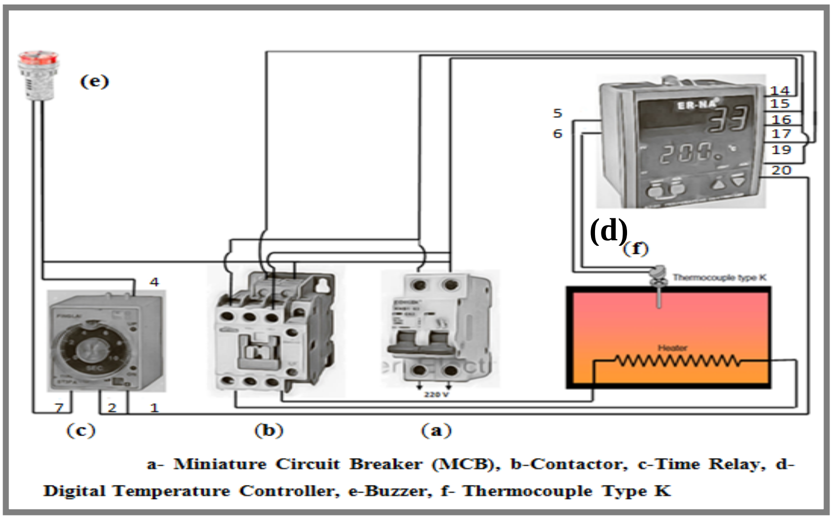


Figure (3): Electrical control circuit

Results and Discussion:

Constant Creep-Fatigue Damage Test

The specimens were tested under constant amplitude fatigue stress at room temperature (RT), 100 ^{o}C and 200 ^{o}C to estimate the S-N curves .The results of this series are illustrated in Table (4) and Figure (4).

Table (4): Constant amplitude fatigue results at different temperatures

Temperature (^{O}C)	Stress (MPa)	N_f (Cycle)	$N_{av.}$(Cycle)
RT	250	14000,16000, 21000	17000
	225	29000,34000,42000	35000
	200	68000,76000 ,87000	77000
	150	500000,520000,567000	529000
100	250	8000, 10000, 11000	9667
	225	14000, 18000, 23000	18333
	200	52000, 45000,41000	46000
	150	375000, 330000,313000	339333
200	250	7000, 9000, 11000	9000
	225	11000, 12000, 13000	12000
	200	26000, 33000, 47000	35333
	150	250000,221000, 216000	229000

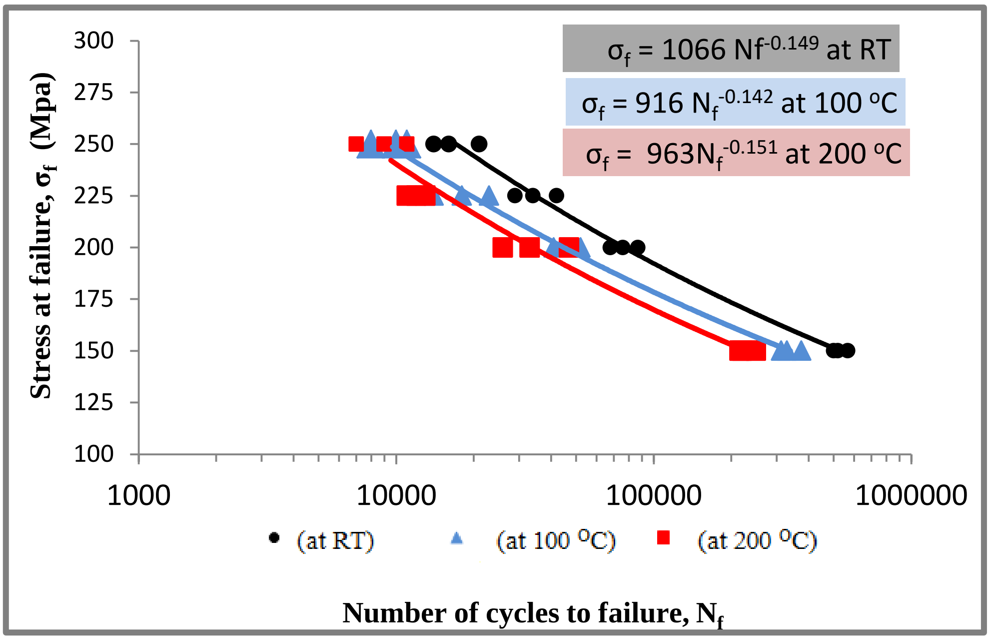


Figure (4): Basic S-N curves for AA7349 at different temperature

The equations of aluminum alloy (AA7349) could be written in the basquin equation form as follows;

$\sigma_f = 1066\, N_f^{-0.149}$ at RT …(2)

$\sigma_f = 916\, N_f^{-0.142}$ at 100 °C …(3)

$\sigma_f = 963\, N_f^{-0.151}$ at 200 °C … (4)

These equations have shown that, for a given stress value, the number of cycles that cause failure decreases in about 55% with the increase of the temperature. These results are consistent with the findings of Ref. [5].

The endurance limits of the material used in different temperature are given in Table (5) and the effect of temperature on fatigue endurance limit stress shown in Figure (5).

Table (5): Endurance limit of AA7349 at different temperatures

Temperature in °C	Fatigue Endurance limit (MPa) at 10^7	Reduction in Fatigue Endurance limit strength RS%
RT	97	-
100	93	4.3
200	85	14.1

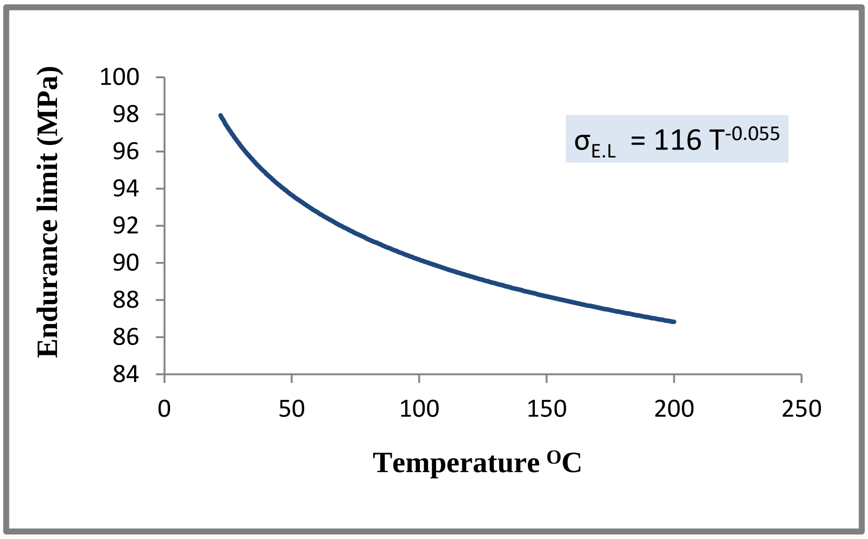
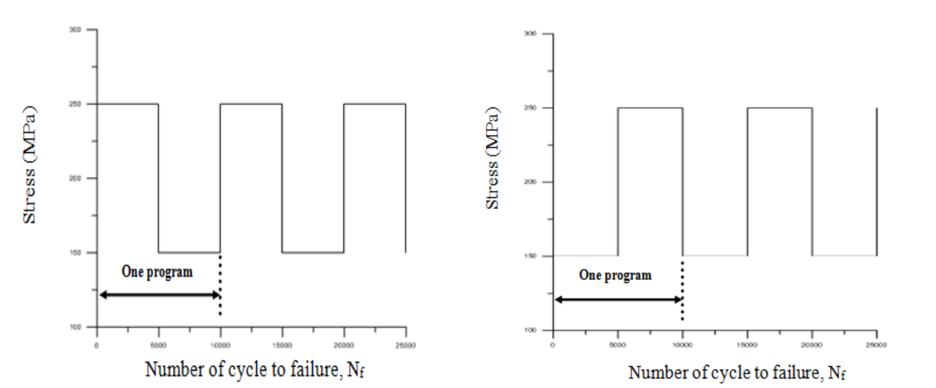


Figure (5): The fatigue endurance limit stress for AA7349 alloy at different temperatures.

The results showed that the increase in temperature leads to a decrease in fatigue limit. These findings are in good agreements with concluded remarks of Ref. [7].

Cumulative Creep-Fatigue Damage Test:

This group is selected in order to investigate the variable creep-fatigue interaction at room temperature (RT), 100 °C and 200 °C, the specimens tested under high to low stress (H-L) and low to high stress (L-H), as shown in Figure (6 a, b). The results of this series are illustrated in Table (6). These results show that the fatigue life at fracture N_f during the low-high sequence is larger than that of high-low sequence this may be due to crack growth in high-low load sequence and that agrees with the finding of Ref. [16].



(a) H – L Program **(b) L – H Program**

Figure (6): Load sequence of Variable amplitude creep-fatigue interaction test

Table (6): Variable creep-fatigue interaction test at different temperatures

Temperature °C	**Stress level (MPa)**		**N_f (Cycles)**	**$N_{av.}$ (Cycles)**
RT	150	Q	63000	60000
			61000	
			56000	
	250	150	51000	45000
			43000	
			41000	
100	150	250	57000	53000
			53000	
			49000	
	250	150	40000	37333
			38000	
			34000	
200	150	250	38000	36333
			36000	
			35000	
	250	150	42000	32000
			32000	
			22000	

Life Estimation Using Miner Rule

Among all the fatigue damage accumulation rules, the LDR (linear damage accumulation rule), also known as Palmgren–Miner's rule, is probably the most commonly used. Miner expressed the fatigue damage accumulation under variable loadings as

$$D = \sum_{i=1}^{K} \frac{n_i}{N_i} \qquad (5)$$

Where; D is the fatigue damage of the material, n_i is the number of applied loading cycles corresponding to the ith load level, $5*10^3$ cycle in the selected program here, N_i is the number of cycles to failure at the ith load level, from constant amplitude experiments [17]. Salah [15] found that the Miner rule does not give accurate and reliable predictions for fatigue lives of AA5086-O, AA6061- T651and AA7075-T651 at 250 ^{O}C due to the following reasons [18]:

1- The fundamental shortcoming of the Miner rule is that fatigue damage is indicated by a single damage parameter only viz n/Nf, which accumulates from zero to unity at failure.
2-Miner rule ignores the loading sequence interaction
3- Miner rule neglects the environment effect.
Despite all those deficiencies, LDR is still frequently used due to its simplicity [17].
The results of miner rule are illustrated in Table (7). The fatigue life prediction based on linear damage rule was compared to the actual life and gave good agreement.

Life Estimation Using Proposed Model

In this study, creep-fatigue damage parameter D_{CF} which can be defined by:

$$D_{CF} = \left[\frac{n}{N_f}\Big|\,\text{high} + \frac{n}{N_f}\Big|\,\text{low}\right]^{\alpha\frac{\sigma_L}{\sigma_H}} \quad \ldots\ldots \text{ for low – high program} \qquad (6)$$

$$D_{CF} = \left[\frac{n}{N_f}\Big|\,\text{high} + \frac{n}{N_f}\Big|\,\text{low}\right]^{\alpha\frac{\sigma_H}{\sigma_L}} \quad \ldots\ldots \text{ for high – low program} \qquad (7)$$

Where;D_{CF} is the cumulative damage parameter, n_i is the number of applied loading cycles, $5*10^3$ cycle in the selected program here, N_i is the number of cycles to failure at the ith load level, σ_H is the high stress level applied, σ_L is the low stress level applied and α is a material constant form the S-N curve depending on the testing condition.
The results of the fatigue-creep interaction are compiled in Table (7). The proposed model Equations (6, 7) which takes the effect of loading sequence and the test environment into consideration shows that a much better and conservative prediction of lifetime compared to the experimental ones.

Table (7): Comparison between proposed models, experimental and Miner lives and damage parameter at 100 ^{O}C and 200 ^{O}C.

Temperature (^{O}C)	Stress level (MPa)		$N_{f(Exp)}$ (Cycles)	$N_{f\,(Miner)}$ (Cycles)	$N_{f(Proposed)}$ (Cycles)	D_{CF}	D_{Miner}
RT	150	250	60000	32362	29395	0.899	1
	250	150	45000	32362	24363	0.744	1
100	150	250	53000	18248	17335	0.95	1
	250	150	37333	18248	15769	0.867	1
200	150	250	36333	14631	14492	0.963	1
	250	150	32000	14631	13564	0.902	1

Figure (7) presents a comparison between creep-fatigue interaction life estimated experimentally, Miner rule and proposed model.

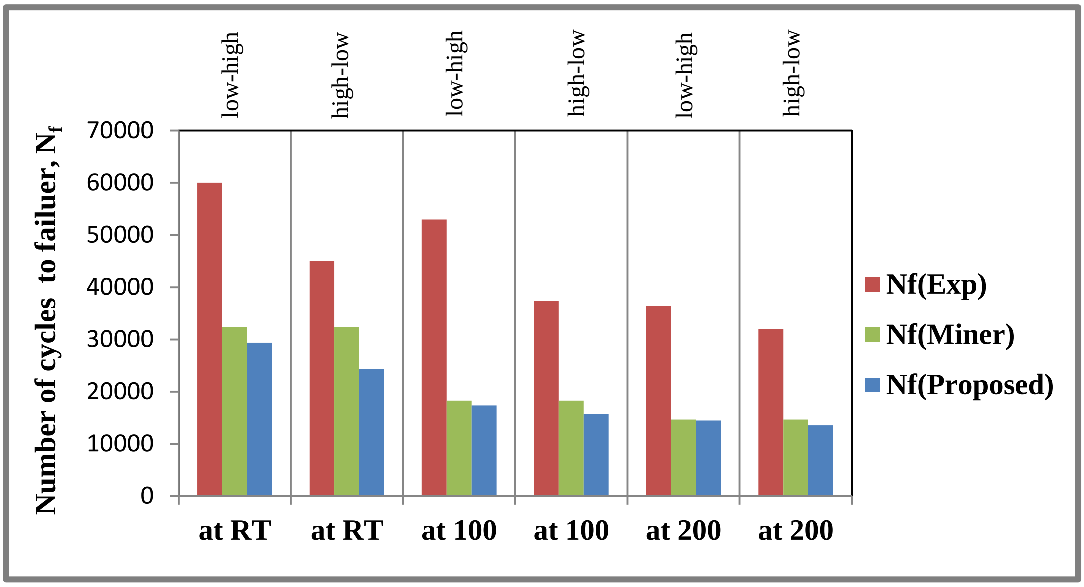


Figure (7): Comparison between proposed models, experimental and Miner lives of AA7349.

Conclusions:

The behavior of aluminum alloy (AA7349) under creep-fatigue interaction is investigated under stress ratio R=-1, and following conclusions could be derived from this investigation;

1-The electrical control circuit was designed and tested for controlling the temperature inside the furnace to investigate fatigue - creep interaction it worked successfully and gave promising results.

2- In constant amplitude fatigue tests, the fatigue life is inversely proportional to stress, while in variable amplitude fatigue tests the fatigue life at fracture N_f during the low-high sequence is larger than that of high-low sequence.

3- The experimental results indicate that the aluminum alloy AA7349 has reduction in fatigue life in about 55% at 200 ^{O}C as a compare to a room temperature value.

4- The fatigue strength reduced by 4.3% at 100 ^{O}C and 14.1% at 200 ^{O}C compared with that at room temperature.

5- Satisfactory predictions have been obtained from applying the proposed model and Miner rule.

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