Thermo-Mechanical Fatigue (TMF) Model for (2017-T4) Aluminum Alloy under Variable Temperature

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Abstract

In this work, constant and increasing temperature fatigue interaction effect on fatigue behavior of 2017-T4 aluminum alloy was investigated. Fatigue tests at constant load constant temperature and constant load increasing temperature were performed for five applied stresses which are (350,275,200,175 and 150 MPa) that based on the tensile test behavior .The constant temperatures were room temperature (RT) (25℃) and 100℃. While the increasing temperatures were RT, 50℃, 100℃ and 150℃ for one test program. The constant fatigue property of the increasing temperatures was observed the worst case compared to the others constant fatigue properties. A new variable temperature fatigue damage model was proposed. It is based on the S-N curve and taking into account the effects of constant loads and variable temperature. A comparison between prediction of the proposed model and crack growth rate due to Miner rule was made. The results proved that this model is satisfactory and gave safe results than Miner rule compared to experimental data.

Keywords: Thermo-Mechanical Fatigue; 2017-T4 Al alloy; Variable Temperature Model.

1 Introduction

Fatigue can be defined as one of the most important damage mechanisms for structures working at elevated temperatures. Crack initiation and crack growth and larger strain deformation may be caused by fatigue at high temperature leading to failure of the material because of mechanical and thermal strains, so the materials must have good mechanical properties in order to be used in such severe environments [1]. The damage of the component is affected by the changes in the rate of temperature. When the temperature change is severe even when there is no mechanical loading, plastic deformation is produced resulting in crack initiation in ($5x10^4$) or less cycle [2].The trouble of thermo-mechanical fatigue (TMF) life prediction has received large attention in recent years, with the efforts principally focus on the prediction of (TMF) under uniformly repeated loading cases. Many studies have developed models to address this problem, generally based on isothermal (IT) regard. Isothermal tests do not clear picture for all damage mechanisms that work under variable strain-temperature cases [3]. Bahaideen et.al (2009)[1] studied fatigue behavior of aluminum alloy (2024 – T4) under room and elevated temperatures and observed that the fatigue strength of 2024 – T4 Aluminum alloy at elevated temperature is reduced by a factor 1.2 – 1.4 compared with dry fatigue strength. Al-alkawi, et.al (2011)[4] studied the effect of two different temperatures (room temperature and 200 °C) in the tests on 1100 Aluminum alloy in order to analyze the influence of temperature on fatigue strength. Fatigue life (S-N curves) for two different temperatures were conducted experimentally .The experimental results showed that the fatigue strength at a given number of cycles reduces with increase in temperature. Costa and Silva (2011) [5] presented the fatigue strength of nodular cast iron at temperatures (20,150,300,450)˚C .The experimental results were showed, no change in fatigue strength for specimen tested at 20 and 150˚C, whereas the fatigue strength increases for specimens were tested at 300˚C, and then reduces when tested at 450 ˚C. This research was showed the opposite tendency of fatigue limit and tensile strength with temperature. Hantoosh et.al (2012)[6] studied accumulation damage for 2024-T4 aluminum alloy. The tests were done at RT (25℃) and (200℃). A modified damage model was proposed to predict the fatigue life under elevated temperature which was taken the damage at different load into account. The proposed model results were compared with the experimental results and compared with fatigue damage model (Miners rule). The comparison showed that the proposed model gave reasonable factor of safety while Miner model sometimes presents a factor of safety close to unity. Al-Saraf (2012) [7] presented two aluminum alloy (2024 and 5052) at stress ratio R = -1 and rotary bending load for obtained the fatigue endurance limit which were carried out at (RT, 100℃, 200℃ and 300 °C) in order to conduct the S–N curve equations. The results showed that the fatigue endurance limit reduce with increasing the temperature. Also the reduction proportion in fatigue endurance limit for 5052 AA was higher than of 2024 AA. The aim of this study is to investigate the effect of thermo-mechanical fatigue on 2017-T4 Al-alloy and proposed a new model for (TMF) at variable temperature condition**.**

2 Experimental Work

2.1 Material Used and Chemical Analysis

The material studied in the current work was 2017-T4 aluminum alloy. This alloy was the first developed in the Al-Cu-Mg series, that used in chiefly for rivets in components for general engineering purposes, structural applications in transportation and construction, machine products, screw, and fittings. This alloy has general characteristics as (Age-hardenable wrought aluminum alloy with medium strength and ductility, good machinability, good formability, and fair resistance to atmospheric corrosion [8]. The physical and thermal properties of the 2017-T4 aluminum alloy are 2.80 g/cm^3 density , 513-641 ℃ melting point , thermal conductivity is 134 W/m.℃ at 25℃ with T4 Temper and thermal expansion of 23.6 x10^{-6} µm/m.C at 20-100℃ [8]. Chemical composition of tested material (2017-T4 aluminum alloy) was performed in the (State Company for Inspection and Engineering Rehabilitation in Iraq) (SCIER) .The results are compared with American Standard Test Method (ASTM B-211), and listed in the Table 1.

Table 1: Chemical Composition of 2017-T4 aluminum alloy in wt %.

Material 2017-T4 AA	Chemical Composition								
	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
Standard ASTM B-211[8]	0.2-0.8	Max. 0.7	3.5-4.5	0.4-1	0.4-0.8	Max . 0.1	Max. 0.25	Max. 0.15	Balance
Actual	0.21	0.61	4.1	0.62	0.7	0.04	0.25	0.1	Balance

The mechanical properties of 2017-T4 aluminum alloy obtained from the tensile test are shown in Table 2.

Table 2: The mechanical properties of 2017-T4 aluminum alloy.

Yield stress (σ_y) (MPa)	Tensile strength (σ_u) (MPa)	Elonga -tion %	Modulus of elasticity (E) (GPa)
275	274	22	72.4
265	425	21	72

2.2 Fatigue Tests

The fatigue tests can be separated into two categories, which includes dry fatigue at (RT) and thermal fatigue tests. All tests were performed under constant amplitude stress level and at different temperatures. Fatigue test was performed by using fatigue test machine of type (PUNN rotating bending). The fatigue test specimens prepared according to the (DIN 50113) standard specification. The standard specimen and testing apparatus are illustrated in Figures 1 and 2, respectively .This test was carried out in (University of Technology /Electromechanical Engineering Department).

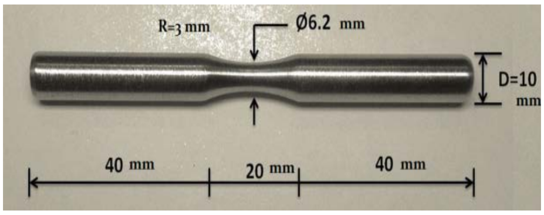

Figure 1: Fatigue test specimen according to the ASTM81-8 standard specification. [9]

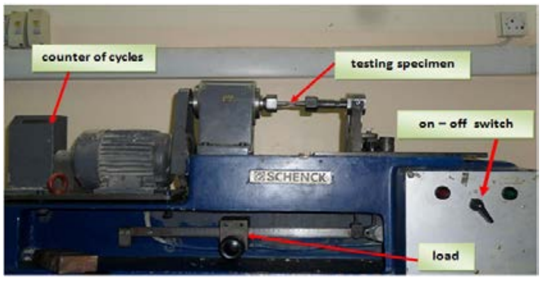

Figure 2: Fatigue testing apparatus.

2.3 Thermal Device

Fatigue at elevated temperature required a thermal device for heating the environment of the specimens to a known elevated temperature. An electric furnace is manufactured with suitable dimensions of (100×120×140) mm. 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. An electrical heater of (2000W) is fastened inside the furnace with a K-type thermocouple for the sake of control to heating temperature inside the furnace [10]. The thermocouple is attached to the thermal control unit board and the furnace.

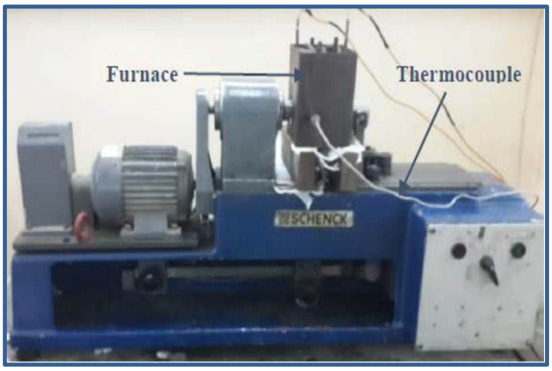

Figure 3: Furnace attached to fatigue machine.

3 Experimental Data and Discussion

Three tests carried out at (R = -1) and (350,275,200,175 and 150 MPa) applied stresses that based on the tensile test behavior, in order to cover the high cycle fatigue region. These tests will be presented and discussed below:

3.1 Constant Amplitude Load at RT (25℃)

Fatigue test was performed at room temperature and the load remained constant until the failure of the specimens occurred. When specimen failed the fatigue testing be automatically stopped. (12) specimens were tested using four stress levels (350,275,200 175 and 150 MPa) .Three tests were performed at each of these stress levels and the number of cycles until failure were recorded by a mechanical counter which is coupled directly to the drive shaft of the d.c. motor. The results of this test are shown in the Table 3.

Table 3: Dry Fatigue Test at RT (25℃) using 2017-T4 Aluminum Alloy.

Speci-mens No.	Applied Stress (MPa)	Cycles to Failure (N_f) at Dry fatigue	Average Cycles $N_{f\ av.}$
1,2,3	350	2000,9000, 5000	5333
4,5,6	275	97000,49000, 20000	55333
7,8,9	200	460000,1930, 268000	307000
10,11, 12	175	388000,7910, 90000	423000
13,14, 15	150	1740000, 1860000,166 0000	1753333

3.2 Constant Amplitude Load at Constant Temperature (100℃)

The fatigue test at constant amplitude load and constant temperature (100℃) was achieved using (12) specimens tested at the same stress level mentioned above .The test specimen environment heated till the digital electrical control circuit reached the temperature 100℃ , then the fatigue machine start to operate. In order to examine the temperature of specimen surface, a thermocouple was holed to the furnace and it can be measure the temperature at specimen surface. Table 4 illustrates the results of this group.

Table 4: Fatigue Test at Constant Temperature (100℃)

Speci-mens No.	Applied Stress (MPa)	Cycles to Failure (N_f) at Constant Temp. (100°C)	Average Cycles $N_{f\ av.}$
16,17, 18	350	1000,4000, 4000	35000
19,20, 21	275	38000,13000, 12000	21000
22,23, 24	200	174000,115000, 66000	118333
25,26, 27	175	126000,59000, 421000	202000
28,29,	150	790000,781000,	791000

3.3 Constant Amplitude Load at Variable Temperature 25℃, 50℃, 100℃, 150℃

(12) specimen were tested under variable temperature and constant applied stress. Table 5 shows the results of this test, the diagram shown in Figure 4 outlines the details of the tests.

Table 5: Fatigue Test Results at Variable Temperature (25℃, 50℃,100℃,150℃)

Speci-mens No.	Applied Stress (MPa)	Cycles to Failure(N_f) at variable temp.	Average Cycles $N_{f\ av.}$
31,32, 33	350	2000,3200, 2600	2600
34,35, 36	275	12600,15000, 18000	15200
37,38, 39	200	34500,36000, 29000	33166
40,41, 42	175	62000,76000, 68000	68666
43,44, 45	150	150600, 144000, 162000	152200

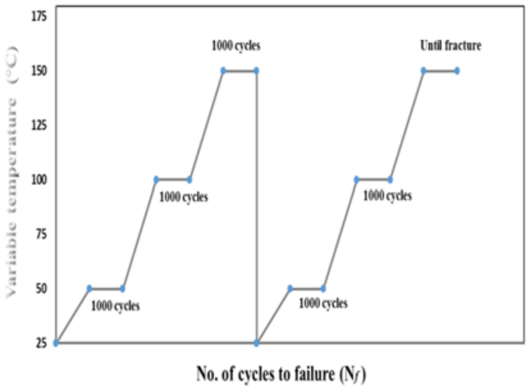

Figure 4: Variable Temperature Constant Stress Amplitude Fatigue Test Diagram.

Figure 5 proved that the test at variable temperature is the worst compared to the dry and constant (100 ˚C) fatigue tests. The reduction of fatigue strength at variable temperature and at constant (100 ˚C) was (47 % ,10.43%) respectively compared to the dry fatigue test .Bahaideen et.al (2009) [1] studied fatigue behavior of aluminum alloy (2024 – T4) under room and elevated temperatures and observed that the fatigue strength of 2024 – T4 Aluminum alloy at elevated temperature is reduced by a factor 1.2 – 1.4 compared with dry fatigue strength. Al-Saraf (2012) [7] presented two aluminum alloy (2024 and 5052) at stress ratio R = -1 and rotary bending load for obtained the fatigue endurance limit which were carried out at (RT, 100℃, 200℃ and 300 °C) in order to conducted the S–N curve equations. The results showed that the fatigue endurance limit reduce with increasing the temperature.

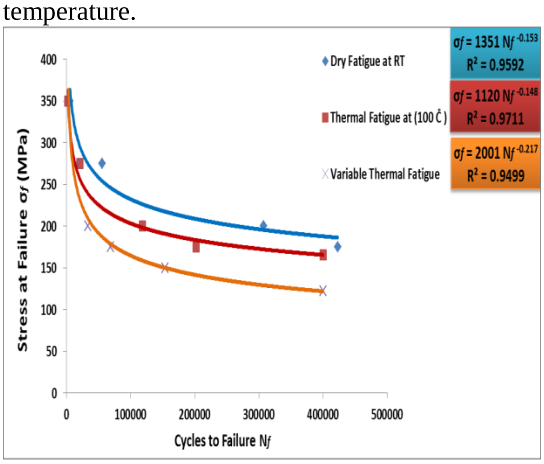

Figure 5: S-N Curve for Three Fatigue Test Conditions.

4 Crack Growth Rate According to Miner Rule

Miner [11] defined damage due to fatigue is crack length (a) and the damage rate is da /dN. Consider ,for example the work of Frost [12] who has shown that over a wide range of materials crack growth of long cracks (crack propagation) can be presented in the Equation (1).

$$\frac{da}{dN} = A\Delta\sigma^{\beta} a \qquad (1)$$

Where A and β are material constants dependent on temperature. After integration from a = R_a (roughness of the specimen surface) to a_f =6.2 mm ,the min. diameter of fatigue specimen and N=0 to N=N_f (cycles at failure) .Equation (2) becomes

$$N_f = \frac{\log\frac{a_f}{R_a}}{A\Delta\sigma^{\beta}} \qquad (2)$$

Where Δσ = 2σ for R=-1

Following the work Delorios et.al [13],they obtained the values of A=4x10^{-11} and β=2 for aluminum alloy. Applying these values to the above equation (3), which can rewritten as

$$N_f = \frac{\log\frac{a_f}{R_a}}{4x10^{-11}\Delta\sigma^{2}} \qquad (3)$$

4.1 Fatigue Life Prediction Damage Model at Variable Temperature According to Crack Growth Rate Miner Rule

According to Delorios et.al model [13] a non-linear fatigue life model can be proposed under increasing temperature and constant amplitude stress. The proposed model can be written in the Equation (4)

$$N_{ff}^{\beta-1} = \frac{\alpha(\beta-1)}{B\beta} \qquad (4)$$

Where N_{ff} is the fatigue life under increasing temperature constant load α is the rate of temperature in constant load increasing temperature ℃/cycle , (β , B) are material constants which can be obtained experimental.

The Miner rule and proposed model can be applied to the last test (fatigue test at variable temperature). The comparison was made between the results, where it was noted that the fatigue life of the proposed model was reduced clearly. The comparison between results was shown in the table 6.

Table 6: Fatigue Results Comparison of Miner Rule and Proposed Model with Experimental Data.

Specimens No.	Applied Stress (MPa)	Cycles to Failure (N_f) at variable temperature (°C)	($N_{f\ av.}$) Experi-mental	N_f Cycles		α °C/Cycle for Proposed Model
				Miner Model	Proposed Model	
31	350	2000	2600	47402	5689	1.642
32		3200				
33		2600				
34	275	12600	15200	76860	19498	1.397
35		15000				
36		18000				
37	200	34500	33166	145313	28955	0.779
38		36000				
39		29000				
40	175	62000	68666	189796	42675	0.941
41		76000				
42		68000				
43	150	150600	152200	256407	76380	0.66
44		144000				
45		162000				

Results of fatigue test at variable temperature at constant amplitude load clearly indicate that the Miner rule give unsatisfactory estimation of fatigue lives under variable temperatures. Figure 6.shows a comparison between experimental, Miner and proposed model S-N curve.

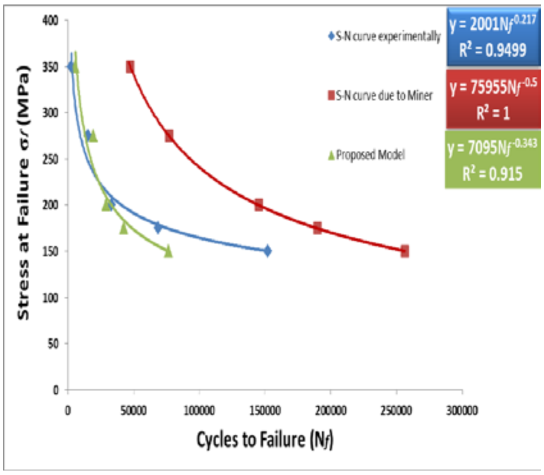

Figure 6. Comparison between the Experimental, Miner and Proposed model S-N Curve.

Marek et.al [14] tested different steel alloys under thermo-mechanical fatigue (TMF) tests and they found that the above steel alloys exhibit lower properties when compared to fatigue only, i.e. fatigue life and strength.

The shortenings between them may come from two reasons are:

- Miner rule assumed damage is linear while it is a non-linear manner.
- Miner rule does not taking into account the effect of temperature change and wet shot peening process.

It is clear that the fatigue life prediction due to Miner overestimated the fatigue lives due to assuming the linear damage equal to unity and neglecting the effect of temperature and surface treatment. A comparison between the fatigue lives prediction of the three methods above can be seen in Figure 7.Two reasons may be made the proposed model results are safely:

- The proposed model designed to be non-linear damage behavior.
- It takes into account the effect of temperature and surface treatment.

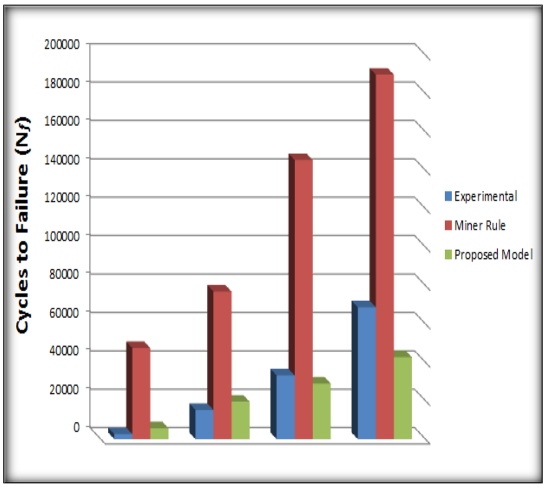

Figure 7. Comparison between Three Methods of Prediction Experimental, Miner Rule and Proposed Model for Fatigue Lives under Thermal Variable Temperature of 2017-T4 Aluminum Alloy

4.2 Proposed Model Results

For constant stress σ = 350 MPa ,The S-N curve equation is $C = 4x10^{7} N_f^{-1.642}$.

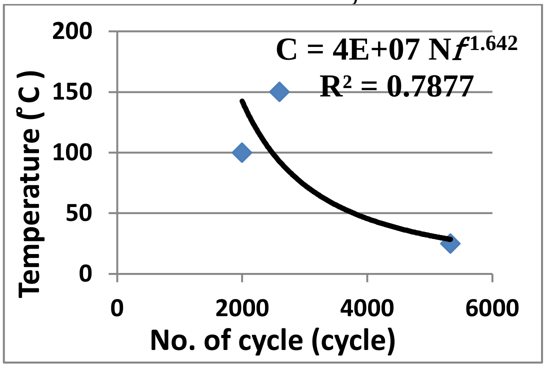

Figure 8: S-N curve equation at constant stress σ = 350 MPa.

$$N_{ff}^{(-1.642-1)} = \frac{3x10^{-3}(-1.642-1)}{4x10^{7}x(-1.642)} = 1.2\ x\ 10^{-10}$$

$$N_{ff} = 10^{3.755} = 5689 \text{ cycle}$$

For constant stress σ = 275 MPa , The S-N curve equation is $C = 1x10^{8} N_f^{-1.397}$.

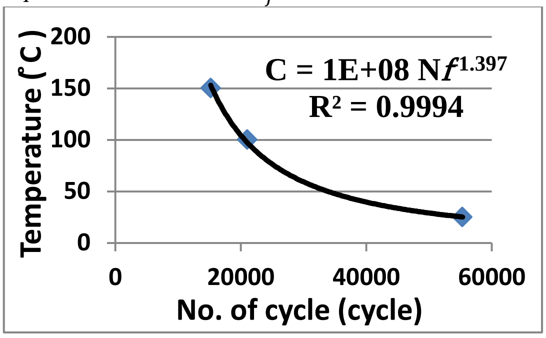

Figure 9: S-N curve equation at constant stress σ = 275 MPa.

$$N_{ff}^{(-1.397-1)} = \frac{3x10^{-3}(-1.397-1)}{1x10^{8}x(-1.397)} = 5.147\ x\ 10^{-11}$$

$$N_{ff} = 10^{4.29} = 19498 \text{ cycle}$$

For constant stress σ = 200 MPa , The S-N curve equation is $C = 593020 N_f^{-1.779}$.

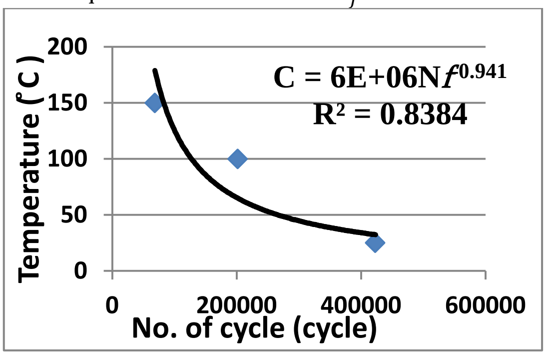

Figure 10: S-N curve equation at constant stress σ = 175 MPa.

$$N_{ff}^{(-0.941-1)} = \frac{3x10^{-3}(-0.941-1)}{6x10^{6}x(-0.941)} = 1.03\ x\ 10^{-9}$$

$$N_{ff} = 10^{4.63} = 42675 \text{ cycle}$$

For constant stress σ = 150 MPa , The S-N curve equation is $C = 465418 N_f^{-0.66}$.

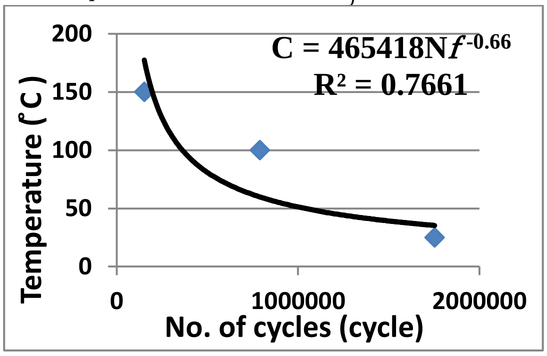

Figure 11: S-N curve equation at constant stress σ = 150 MPa.

$$N_{ff}^{(-0.66-1)} = \frac{3x10^{-3}(-0.66-1)}{593020\ x(-0.66)} = 1.62\ x\ 10^{-8}$$

$$N_{ff} = 10^{4.693} = 49317 \text{ cycle}$$

Many components are subjected to stress and temperature conditions and cyclic processes may not be as dominant as time-dependent processes. Thus in creep rupture design, time fracture rules of the form

$$\sum \frac{t}{t_f} = 1 \quad (5)$$

Where t is the time and t_f time to failure are frequently employed. However the equation (5) above with equation of Miner $(\sum \frac{n}{N_f} = 1)$ can be combined to form

$$\sum \frac{n}{N_f} + \sum \frac{t}{t_f} = 1 \quad (6)$$

are currently in favor for analyzing components that suffer combined time and cyclic deformation processes. Application of equation (6) of linear summation of cyclic fractions to unity were shown to be incorrect for interactions of time and cyclic process while the proposed model gave safe summation and life compared to experimental results [15].

5 Conclusions

The fatigue properties of 2017-T4 aluminum alloy were investigated experimentally at room temperature and variable temperature. The following conclusions may be derived from this study are:

- Fatigue life of 2017-T4 aluminum alloy was reduced with increasing of temperature.
- The worst case of fatigue life was observed at increasing temperature condition.

- Fatigue strength at 100℃ reduced by 10.43 % compared to (RT) case.
- Fatigue strength of increasing temperature case revealed lower strength compared to the constant temperature condition ,and the reduction in fatigue strength due to increasing temperature was 46.95 % compared to (RT) condition.
- Miner rule is not capable to predict the fatigue life at elevated temperatures and it gave underestimation of life prediction.
- A model for fatigue life prediction at variable temperature for 2017-T4 aluminum alloy was proposed. This model is satisfactory and gave safe results than Miner rule compared to experimental data.

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نموذج الكلال الحراري الميكانيكي لسبيكة الالمنيوم 2017-T4 تحت تاثير الحرارة المتغيرة

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الخلاصة

في هذا العمل تم دراسة تاثيردرجات الحرارة العالية والثابتة على سلوك الكلال لسبيكة الالمنيوم 2017-T4. نفذت اختبارات الكلال لاحمال ثابتة وحرارة ثابتة واحمال ثابتة وحرارة مرتفعة لخمس اجهادات مسلطة وهي (350,275,200,175,150)MPa .كانت درجات الحرارة الثابتة تتضمن درجة حرارة الغرفة (RT) و(100 ℃) بينما درجات الحرارة المرتفعة كانت ℃ (150,100,50 ,RT) لبرنامج اختبار واحد.لوحظ انه خواص الكلال عند درجات الحرارة المرتفعة كانت اسوء حالة مقارنة مع خواص الكلال لحالات اخرى.تم اقتراح انموذج جديد لضرر الكلال عند درجات الحرارة المرتفعة معتمدا على سلوك منحني (S-N) اعتمادا على تاثير الاحمال الثابتة والحرارة المرتفعة .تمت مقارنة الانموذج المقترح ومعدل نمو الشق لماينر واثبتت النتائج صحة الانموذج حيث اعطى نتائج امنة مقارنة مع قانون ماينر ونتائج العملي.