Fatigue Performance of 2017-T4 AL. Alloy Under sub-zero Temperature by Using Electromechanical Freezing System

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ABSTRACT

The effects of sub-zero(-22C^o) cyclic rotating bending on the S-N behavior and cumulative damage are reported for 207-T4 aluminum alloy .Experimental characterization of fatigue behavior showed that the S-N curves behavior may described by the following Basquin's formulas:

At room temperature (RT)

And

At sub-zero temperature (-22C^o)

From the above equation, the fatigue behavior can be change at $\sigma_f = 204\ MPa$ and

.

Slightly increase in fatigue life results above 204 MPa and slightly decrease in fatigue below the 204 MPa stress level. A non-linear experimental law is introduced for the accumulation of damage at sub-zero temperature variable fatigue. This law gave conservative and safe fatigue life time prediction when applying to the data of variable fatigue at low temperature (-22 C^o).

Keywords: Fatigue behavior at sub-zero temperature, Cumulative fatigue damage, 2017-T4 AL alloy.

INTRODUCTION

Material fatigue1 is a failure1 mode that has been known to researchers and engineers since the 19th century. Catastrophic accidents have happened due to fatigue failures of structures, machinery and transport vehicles [1].

Fatigue is commonly referred to as a process in which damage is accumulated in a material undergoing fluctuating loading, eventually resulting in failure, even if the maximum load is well below the elastic limit of the material. Fatigue refers to the process which reduces local strength of engineering, materials [2].

Failure occurring under dynamic conditions of stress application are known as fatigue failure. Fatigue failure is rather unpredictable because it happens without notice [3].

Fatigue failure causes (1) Fatigue failure is due to repeated loading: At least half of all mechanical failures are due to fatigue. Many books and articles have suggested between 50 and 90 percent of all mechanical failures are fatigue failures (2) Most of these are unexpected failures. They include simple items such as door springs and electric light bulbs to complex

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components and structures involving ground vehicles, ships, aircraft and human body implants. Examples are automobile steering linkage, engine connecting rods, ship propeller shafts, pressurized airplane fuselage, landing gears and hip replacement prostheses [4].

Mechanical and physical properties of aluminum and aluminum alloys change when working temperature change from cryogenic ($-195C^0$) to elevated temperatures (max. $400C^O$). These changes are not so intensive compared to another materials such as steel and others. Changes of properties of aluminum alloys with temperature depend on chemical composition and temper. Alloys of the 2xxx series such as 2014 and 2024 perform better above these temperatures but are not normally used for elevated-temperature applications [5].

Low-Temperature Properties Aluminum alloys represent a very important class of structural metals for subzero-temperature applications and are used for structural parts for operation at temperatures as low as $-270C^O$.[5]

Below zero, most aluminum alloys show little change in properties; yield and tensile strengths may increase; elongation may decrease slightly; impact strength remains approximately constant. Consequently, aluminum is useful material for many low-temperature applications.[5]

The chief deterrent is its relatively low elongation compared with certain austenitic ferrous alloys. This inhibiting factor affects principally industries that must work with public safety codes. A notable exception to this has been the approval, in the ASME unfired pressure vessel code to use alloys 5083 and 5456 for pressure vessels within the range from -195 to $65C^o$. With these alloys tensile strength increases 30 to 40%, yield strength 5 to 10% and elongation 60 to 100% between room temperature and $-195C^o$[5].

The wrought alloys most often considered for low-temperature service are alloys 1100, 2014, 2024, 2219, 3003, 5083, 5456, 6061, 7005, 7039 and 7075. Alloy 5083-O which is the most widely used aluminum alloy for cryogenic applications, exhibits the following cooled from room temperature to the boiling point of nitrogen ($-195C^o$):

- About 40% in ultimate tensile strength
- About 10% in yield strength

The increase in the mechanical properties works to improve the fatigue behavior under constant and variable condition [5].

Experimental Procedures

Material Selection

Aluminum of the 2017-T4 is used in the current work 2017 – Like 2011 (which is free machining alloy compares favorably with free cutting brass. It is the most suitable alloy for machining on automatics, milling machines, lathes, planers, shapers and other machine tools, and is the most widely used alloy for all types' of screw machine parts. It can be machined at high speeds and comparatively heavy feeds). This is also a general-purpose alloy for automatic screw machine work. It is stronger than 2011, but harder to machine and does not have the fine chip associated with 2011. It is recommended for heavy-duty parts because of its high strength. Workability is fair, with ductility and formability considered better than 2014. Arc and resistance weld ability are satisfactory. Corrosion resistance is fair. It is used for rivets, fasteners, and aircraft components and it is primarily used in applications where electrical conductivity, formability, ductility [6]. Chemical analysis of the metal used was tested at (State Company for Inspection and Engineering Rehabilitation (SIER) in Iraq).The results, which are compared to the American Society for Testing and Materials (ASTM B209) [7], Chemical analysis of the metal used was tested at (State Company for Inspection and Engineering Rehabilitation (SIER) in Iraq) are summarized in Table (1) .

Table (1) Chemical compositions of the 2017 aluminum alloy Wt% (ASTM B209)[7] and according to (SIER) in Iraq.

Material	Si	Fe	Cu	Mn	Mg	Cr	Zn	AL
Standard ASTM B209	0.44	0.25	3.80	0.68	0.56	0.02	0.02	Balance
Actual SIER	0.42	0.26	3.68	0.64	0.53	0.017	0.021	Balance

Tensile test

Tensile tests (three specimens) were accomplished at the department of material Engineering, university of technology .using the test machine WDW-100 with capacity of 100KNwhich is shown the figure (1). The test specimen as in figure (2) is installed between the two large grips of the testing machine and then loaded in tension. Measuring devices record the deformations, and the automatic control and data-processing systems (at the left in the photo) tabulate and graph the results [8].

Below the mechanical properties are listed in Table (2) and the results of the tensile tests are shown in **Fig (3)** .The alloys used in the present study were provided in form of rod of 2017A-T4 alloy.

Table (2) Mechanical properties of the 2017 -T4 aluminum alloy (ASTM B209) [7] and according to (SIER) in Iraq.

Material	Tensile strength (MPa)	Yield strength(MPa)	Elongation (%)	E (GPa)	Poisson's ratio
Standard	440	240	26.3	77	0.3
Actual	452	248	27.2	78	0.3

The above results are the average of three readings.

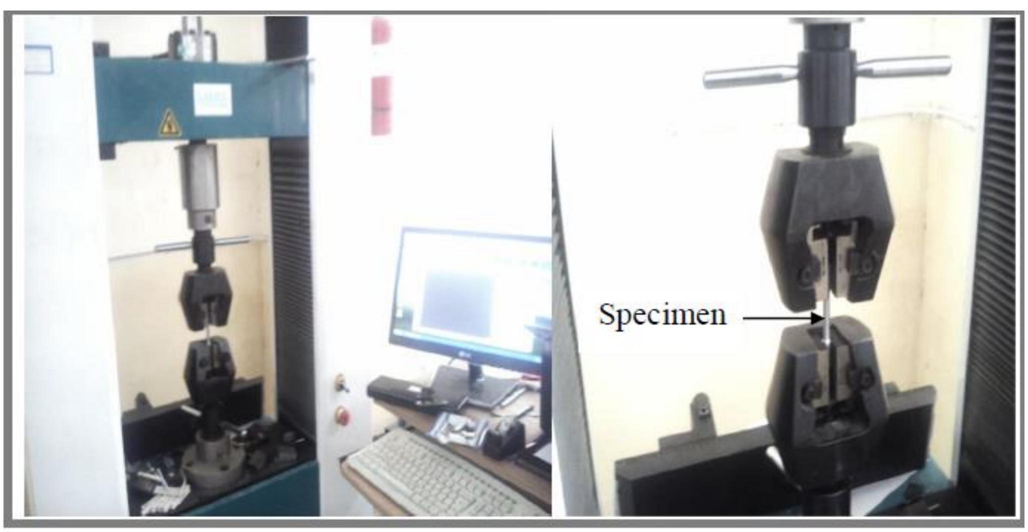

Figure (1) Tensile test machine WDW-100

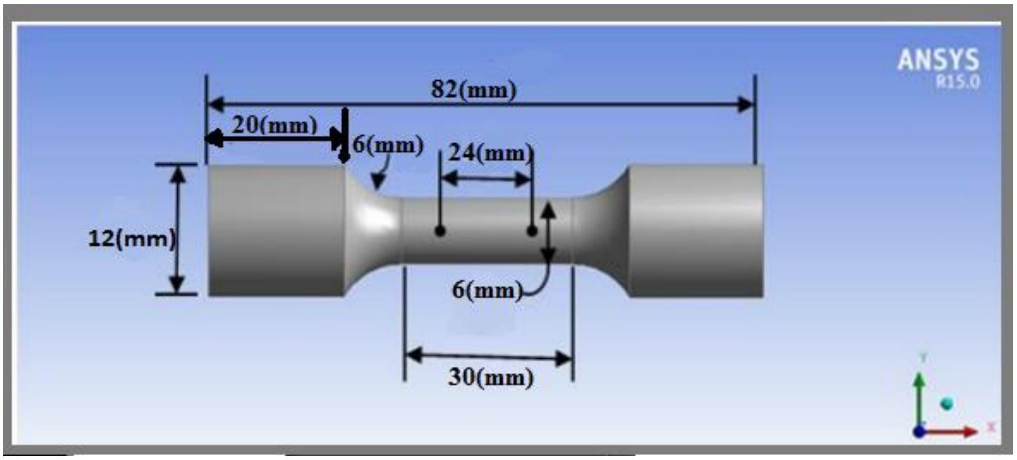

Figure (2) tensile test specimen according to ASTM [7]

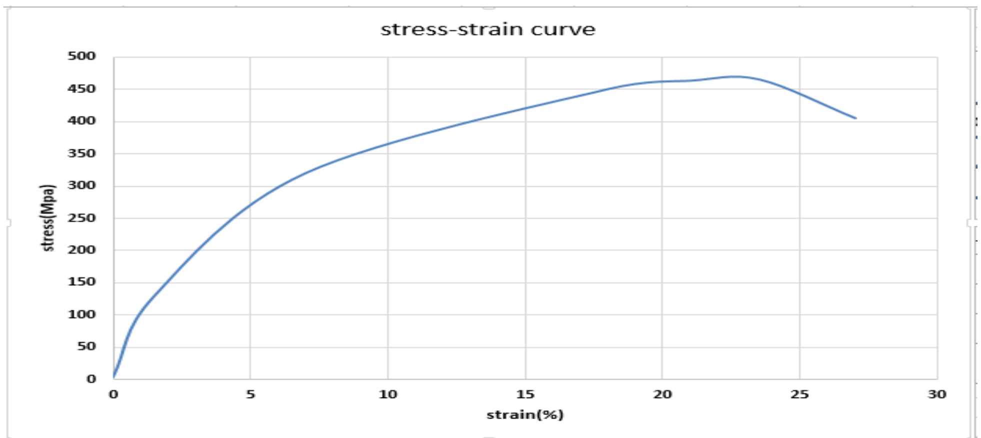

Figure (3) Average results for tensile test of 2017-T4 alloy(average of three specimens).

Fatigue test machine

A reverse bending fatigue machine type Schematic of schench rotating-bending fatigue machine, as shown in Figure (5) was used to carry out the fatigue testing. The tests were undertaken in stress control with a stress ratio R=-1 and the cycling rate is 1420 rpm (f=23.67 Hz).

In this rotating-bending fatigue machine used to calculate the number of cycles that it takes until the specimen fail by recording number of cycles from the cycle counter which is located in the left of the machine. The range of the loads that had been taken through the fatigue test were varied between (150MPa) and (350 MPa) for constant stress level.

Material used in this study is a rod (10mm diameter and 80 mm length) of 2017-T4 aluminum alloy (rod product) for fatigue test at room temperature (RT) and low temperature (-22C^{o}).

Operation freezer with Electrical Control Circuit:

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 freezer measured by the sensor with the desired load temperature (the Set-Point) and actuates the final control device which is a contactor.

system consists of several equipment's like compressor, condenser, evaporator, expansion devices etc. A refrigerant compressor is a machine used to compress the refrigerant from the evaporator and to raise its pressure so that the corresponding temperature is higher than that of the cooling medium. The condenser is an important device used in the high pressure side of a refrigeration system. Its function is to remove heat of the hot vapour refrigerant discharged from the compressor. The evaporator is used in the low pressure side of a refrigeration system [9].

A temperature control system is composed of essential elements which all affect its performance as shown in Figure (4):

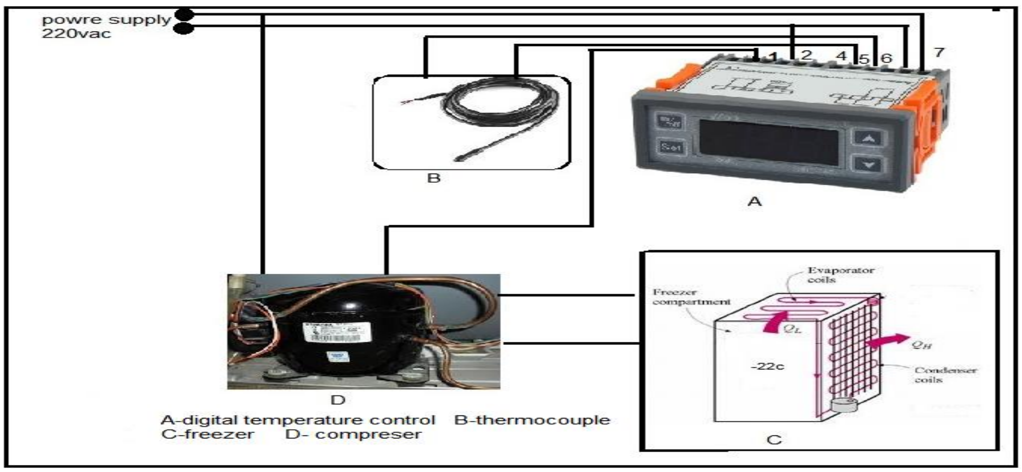

Figure (4) The Electrical controlling circuit.

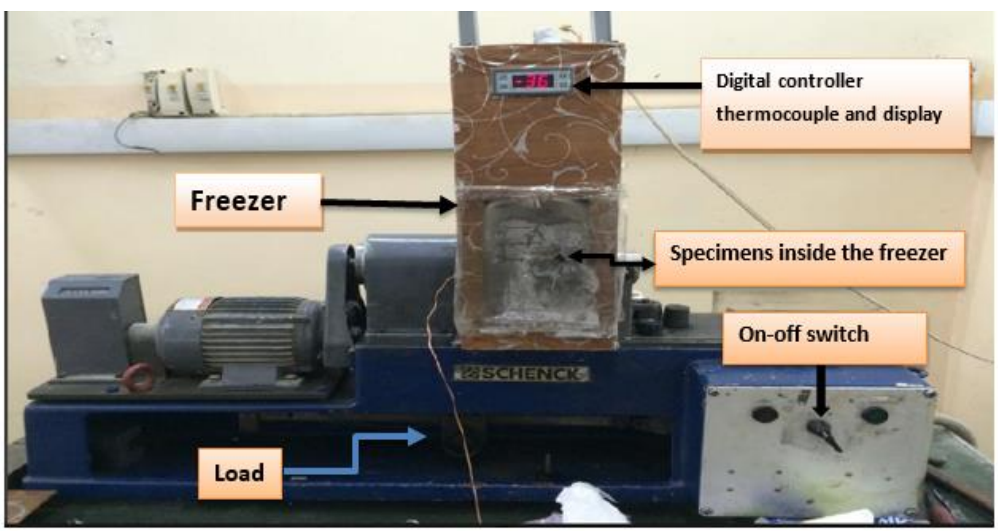

Figure (5) fatigue test machine with freezer

Fatigue specimen

These specimens were cut in suitable dimensions to satisfy the machine test (according to Users 'Instructions Manual) [7]. Figure (6) shows the shape and dimensions of fatigue specimens.

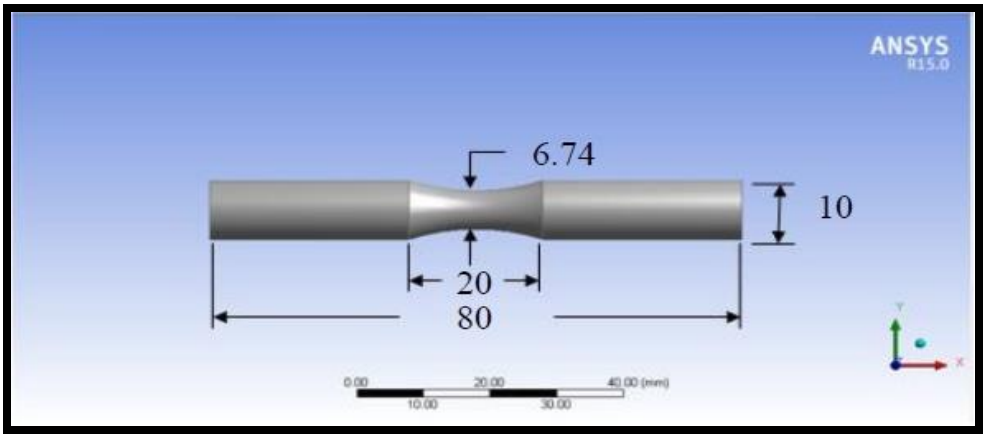

Figure (6) Fatigue test specimen (all dimensions in mm) [7]

Results and discussions

A) S-N Curve Constant Amplitude Fatigue Results

The specimens were tested under constant amplitude fatigue stress control rotating bending at a stress ratio R=-1 at room temperatures (RT) and low temperature (-22C^o) to estimate the S-N curves. The results of this series are illustrated in Figure (7) for aluminum alloy 2017-T4 at room temperature and at sub-zero temperature (-22C^o).

The fatigue tests are presented in the curves shown in Figures (7) these curves give an indication about the variations in fatigue life. From these data, the fatigue life estimation equations were determined. The fatigue endurance limit can be calculated by using these equations. The percentage of enhancement in fatigue life was calculated for all groups.

S-N data for 2017-T4 AL. alloy at low condition of testing namely RT and subzero temperature (-22C^o) is illustrated in table (3).

Table (3) S-N data for 2017-T4 AL. alloy at two condition

	RT(23C^o)	**Subzero temp.(-22C^o)**
Applied stress(MPa)	Nf (No. 0f cycles)	Nf (No. 0f cycles)
350	6000,4000,7000	5000,6000,7000,8000
275	23000,11000,16000	123000,87000,22000,14000,41000
200	326000,113000,147000	192000,114000,186000,61000
150	108000,117000,129000	203000,668000

The fatigue behavior of 2017-T4 AL. alloy under two different conditions is presented in figure (7) and the fatigue parameters for the S-N curve equations$\sigma_N = a_1(\mathrm{N_f})^{\mathrm{n_1}}$ can be shown in table (4).

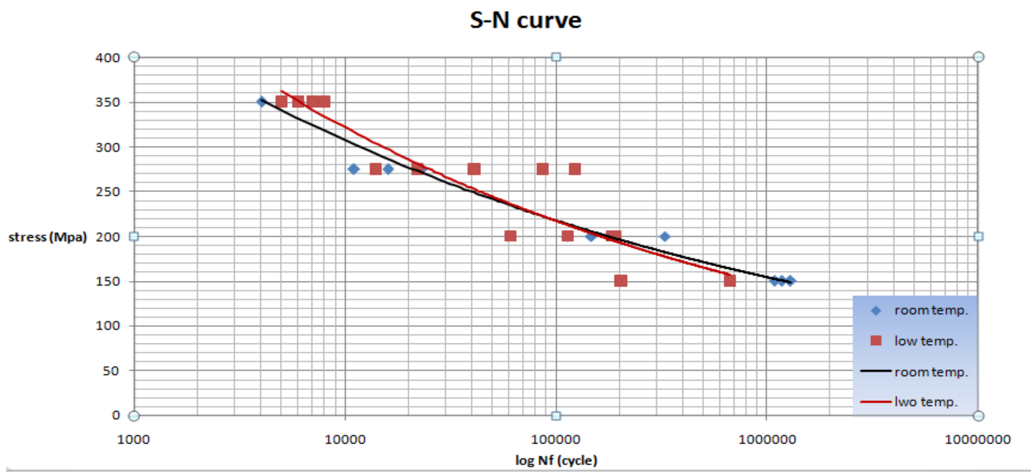

Figure (7) S-N curve for 2017T4 at RT and (-22C^o) temperature.

Table (4) Fatigue parameters of 2017-T4 AL. alloy at two conditions of testing

Test condition	A	α	S-N curve equation	$\sigma_{E.L}$ MPa (fatigue endurance limit)	Reduction in $\sigma_{E.L}$ %
RT(23C^o)	1230	-0.15	$\sigma = 1230 * Nf^{-0.15}$	110	0
Subzero temp.(-22C^o)	1563	-0.17	$\sigma = 1563 * Nf^{-0.17}$	101	8.18

From the fatigue data (experimental) of the specimens (2017-T4) as received and the specimens were cooled to (-22) C^o , then at room temperature , the material (2017-T4 aluminum alloy) with applying stresses (350, 275, 200 and 150) MPa . So figure (8) represent comparison between the two cases to show the values of fatigue limit stress for 2017 aluminum alloy at two cases room temperature and low (-22C^o) .

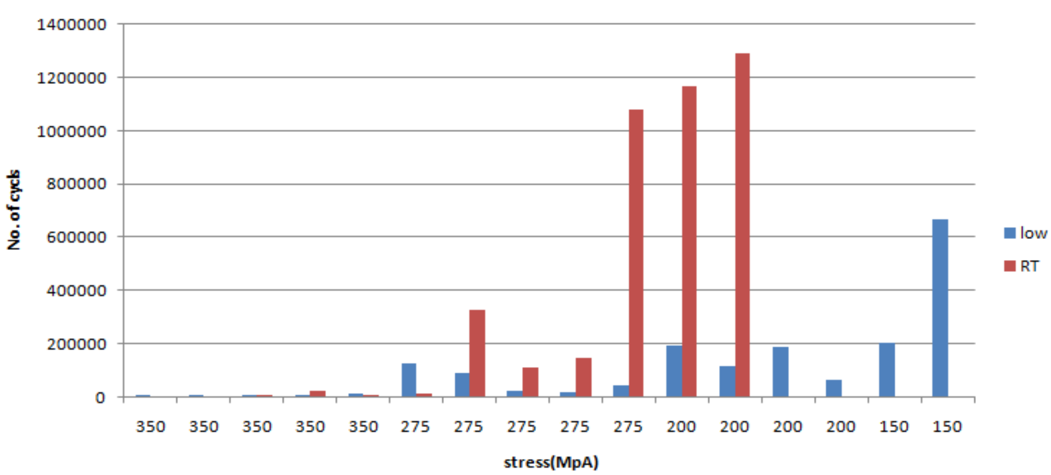

Figure (8) Values of stress fatigue limit for 2017 aluminum alloy

Figure (7) shows the modified S-N curve data for (RT=23C^o) and (-22C^o) above the stress level 204 MPa and number of cycles 159475 the fatigue specimens exhibited increases in the number of cycles to failure (N_f).

While below the 204 MPa stress level the specimens exhibited reduction in the Nf . It is suggested that above the 204 MPa stress level the fatigue resistance increased due to a strong bounding which is the responsible for improvement the fatigue behavior. But below 204 MPa the weakening of bounding exhibited reduction in the fatigue strength lives [10].

So that fatigue endurance limit reduced by 8.18% due to britteness and relaxation of residual stresses or stress concentration [11]. The development and evaluation of fatigue damage in aluminum alloys at low temperature is still an open question [12].

B) Cumulative Fatigue Damage results:

The failure of structural components is difficult to assess, practically when the loading are not constant of light metals (aircraft structure)[13].The prediction of fatigue life of samples subjected to variable loading is a complex subject .For the assessment of fatigue damage under block program loading the most widely used theory is the linear damage rule or ((Miners theory)). This rule has received much attention due to its simplicity [14].

Miners rule implies that damage accumulates linearly with applied cycle fraction, independent of life level. The damage sum is equal to unity according to Miner while the experimental results showed that the damage sum is less or greater than unity. This means that there is no load sequence effect that occurs during the fatigue loading history [15].

It has been verified that light structure can exhibit highly nonlinear fatigue damage evolution. The Miners rule can underestimate or overestimate the fatigue life according to Miners rule, fatigue damage under block loading can be assessed by

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

Where D is the damage equal to unity

K is the number of blocks

Ni is the applied stress cycles

Nfi is the number of cycles to fatigue of block i

For a sequence of two constant blocks

$$D = \frac{n_L}{N_{fL}} + \frac{n_H}{N_{fH}} \qquad \ldots\ldots\ldots (2)$$

Where L is low and H is high stress level.

The non-linear proposed model

Marco and starkey[16] suggest the following non-linear relation :

$$D = \left(\frac{n}{N}\right)^{\alpha} \qquad \ldots\ldots (3)$$

Where α is a function of the applied load which can be determined experimentally.

According to Perieira et al [17] and Alkawi et al [18] ,they defined fatigue damage for low –high and high-low constant block tests as

$$D = \left[\sum \frac{n_i}{N_{fi}}\right]^{x} \qquad \ldots\ldots\ldots\ldots (4)$$

X is defined the effect of loading sequence and surface treatment

For the present work, X may be defined as

$$X = \left[\frac{\sigma_y}{\sigma_u}\right]^{\alpha} \qquad \ldots\ldots\ldots.. (5)$$

For low-high loading

Where α is the basquin exponent determined from the S-N curve equation $\sigma_f = AN_f^{\alpha}$ For sub-zero S-N curve and

$$X = \left[\frac{\sigma_u}{\sigma_y}\right]^{\alpha} \qquad \text{......... (6)}$$

For high-low loading

Finally, equation (4) can be presented to take the form

$$D = [\frac{n}{N_{fL}} + \frac{n}{N_{fH}}]^{\wedge} - (\frac{\sigma y}{\sigma u}\alpha) \qquad \text{...... (7)}$$

for low – high

$$D = [\frac{n}{N_{fH}} + \frac{n}{N_{fL}}]^{\wedge} - (\frac{\sigma u}{\sigma y}\alpha) \qquad \text{...... (8)}$$

for high – low

Applications of Miners rule and proposed model

The experimental results obtained from testing the specimens from low-high and high-low loading sequence can be illustrated in table (4)

Table (4) Experimental fatigue life results for AL-Alloy 2017-T4 under RT (+23)

samples	1,2,3,4,5,6	1,2,3,4,5,6
Loading sequence (MPa)	L -H (200-300)	H-L (300-200)
Nf Cycles	31000,16000,73000, 26000 ,10000,20000,	35000,14000,23000,13000, 12000,41000
Nf.av (cycles)	32500	23000

Table (5) Experimental fatigue life results for AL-Alloy 2017-T4 under (-22C°)

samples	13,14,15,16,17,18	19,20,21,22,23,24
Loading sequence (MPa)	L -H (200-300)	H-L (300-200)
Nf Cycles	28000,38000,29000,44000,27000,38000	26000,32000,37000,18000, 22000,25000
Nf.av (cycles)	34000	26667

It is clear from that the fatigue life of variable amplitude in low-high load sequence is greater than the high-low load sequence life for both conditions RT and (-22C°).Because the specimens is getting hardening due to change from low to high. So, the low to high load sequence is more damaging than high to low loading. These findings are well agreed with References [16] and [19].

Table (6) gives the fatigue life predicted results according to Miner in comparison with the experimental results

Table (6) Comparison between three methods of fatigue life prediction

Loading sequence (MPa)	RT(23)				
	Nf exp. Cycles	Nf Miner Cycles	Nf proposal model Cycles	S.F Miner	S.F Model
L -H (200-300) H-L (300-200)	32500 23000	22807 22807	21313 18207	1.425 1.008	1.524 1.263
	Sub-zero (-22C^{o})				
	Nf exp. Cycles	Nf Miner Cycles	Nf proposal model Cycles	S.F Miner	S.F Model
L -H (200-300) H-L (300-200)	34000 26667	22807 22807	21121 17667	1.49 1.169	1.609 1.509

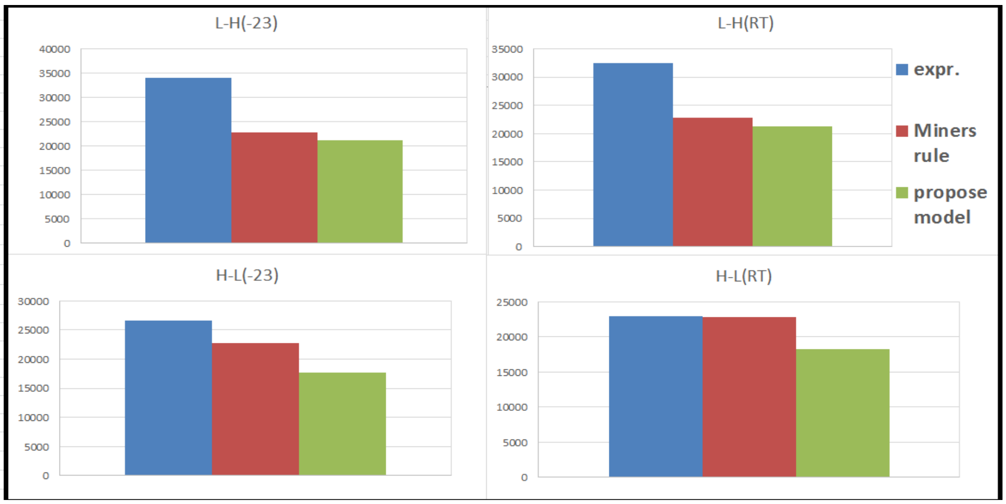

Figure (9) Comparison of fatigue life for two blocks loading, using experimental, miner and proposed model

The figure (9) shows comparison of fatigue life for two blocks loading, using experimental, Miner and proposed model .As seen in the figure, the experimental data for all blocks program loading are greater than the Miner and proposed model. The Miner and proposed model give safe prediction for both conditions of testing RT and (-22C^{o}). This means that the damage is close to unity. The proposed model observed safer than Miner because it works in a non-linear manner. The life prediction based on Miner and proposed model show underestimating the fatigue life with factor of safety slightly greater than unity for Miner rule and from 1.2 to 1.6 for the proposed model. The observation gives an indication that the proposed model is safer in fatigue life prediction compared to Miner theory [20].

CONCLUSIONS

1- The constant fatigue and fatigue damage accumulation for two blocks loading sequence of 2017-T4 Al. alloy was investigated at RT (23C^{o}) and at sub-zero temperature (-22C^{o}).

2- The constant amplitude S-N curve showed change in the behavior of 2017-T4 Al. alloy. The change observed at stress level of 204 MPa and number of cycles 159475. Above this point the sub-zero condition raised the fatigue life while below it reduces the fatigue lives.
3-The fatigue life under two step loading was predicated by Miner rule and proposed model. The two methods give safe prediction compared to experimental results. But the proposed model indicated safer than Miner rule.

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