

Effect of the Elevated Temperature on Fatigue Behavior of Aluminum Alloy AA 7075

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Submission date:- 10/6/2018	Acceptance date:-13/6/2018	Publication date:-24/9/2018
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Abstract

This research presents the effect of fatigue life behavior of aluminum alloy AA 7075 under constant loading amplitude conditions and tested at different temperatures. The prediction of fatigue life using conventional experimental procedures makes the analysis of behavior is real and gives accurate results. The stress-life curves at different temperatures (25, 75, 125, 175 and 225 °C) were estimated. The results for fatigue life at ambient temperature and at elevated temperatures were discussed by the Basquin's relation, and a decrease in fatigue life cycles was found when increasing the testing temperature. Good agreement has been obtained when comparing the current study results with other available experimental data by other studies. A general proposed model (mathematical expression) was formulated to calculate the fatigue life for aluminum alloy AA 7075 at different temperatures. The proposed mathematical model obtained in this study can be used for decreasing the cost and time of the experimental procedures. Also, the Fatigue Life Reduction Factor (FLRF) was increased with increased of the testing temperature at maximum value of (43.963%) occurred at temperature of 225 °C compared with room temperature when applied stress be equal to 540 MPa.

Keywords: Aluminum alloy, Fatigue, high-temperature, Basquin's equation.

1- Introduction

Fatigue failure defined as a permanent damage of engineering structures and materials due to dynamic loads. This phenomenon happens when repeated strains act on a material at a stresses that is well below of its static yield stress. Designers of modern military and commercial aerospace vehicles and space launch systems are constantly in use of best materials with lower density, higher strength, stiffness, besides reasonable cost, with high fatigue resistance and more stable at variable temperatures of application. However, the aluminum alloys have long been preferred for civil and military aircraft due to their having high strength/weight ratio (light weight), excellent weldability, low value of thermal expansion coefficient and excellent corrosion and abrasion resistance. Therefore, these properties of aluminum alloy attribute the rapid increase of using this alloy in automotive structural applications [1], [2].

The fatigue loading effect of the moving components in automotive engines are usually combined together with the temperature effect. Therefore, these components should have high fatigue strength at raised temperatures. The main applications of the vehicle engine parts with high temperature are piston rod, cylinder head, heat exchanger and engine oil pan. Aluminum alloys are usually used in engine components such as piston head. These alloys have high mechanical properties at increased temperatures up to approximately 300 oC [3].

The performance of the fatigue for high temperature deep rolled specimens using fatigue stress tests and compared with the deep rolled at room condition was analyzed by Patiphan and Igor [4]. They were found that deep rolling at high temperature effectively enhances the fatigue behavior of various steels. Also, the deep rolling with high temperature was not entirely effective of aluminum alloy AA5083 where the beneficial effects of strain ageing cannot be fully expected. While Wan, et al. [5] developed a modified new formulae to describe and determine high cycle fatigue behavior of Co-based super-alloy 9CrCo with raised of testing temperatures when considered the effect of stress ratio. The model was built by the relationship between maximum nominal stress, stress ratio and fatigue life. Fatigue tests were performed on Co-based super-alloy 9CrCo subjected to constant amplitude loading at four stress ratios of -1, -0.3, 0.5 and 0.9 in three environments of room temperature, 530 oC, and 620 oC. A reasonable correlation was achieved between predictions and experiments, demonstrating the practical and effective proposed model. The fatigue behavior of aluminum alloy was studied by Farhad,

et al. [6] to derive stress-life equations at elevated temperature. It observed that the life cycles were significantly reduced at elevated temperature with respect to the specimen tested at room temperature for the same applied stress range. It was observed that the fatigue strength at elevated temperature reduced compared to ambient temperature by a factor (1.2-1.4). On other hand, IMAM, et al. [7] carried out the heat treatment effect on the fatigue life and fatigue strength for the aluminum alloy substrate at three level of different temperatures 420 oC, 460 oC, and 500 oC. It was observed that fatigue strength of aluminum alloy increased due to increasing the heat treatment temperature. They concluded that, the dependence of fatigue strength could be linearly related to the temperature dependence of ultimate tensile strength.

From the literature, there is no doubt that the conducting of fatigue tests are usually complicated and time consuming especially when the samples are exposed to different temperatures. Therefore, the fatigue behavior of aluminum alloy at different elevated temperatures will be suggested to studied in this paper, and derive a general mathematical expression to predict the fatigue behavior for aluminum alloy directly without conducting more experimental testes. While, the objective of this study is to investigate the mechanical fatigue behavior of the aluminum alloy AA 7075 experimentally. The range of testing temperatures is from room temperature 25 oC to 225 oC with a step of 50 oC. The experiments are conducted at constant stress amplitude with a stress ratio of $R = -1$ and a constant frequency is equal to 50 Hz. The experimental data will be used to express the stress-life curve at different temperatures and then the Basquin's equation including testing temperature will be constructed mathematically.

2- Materials and Method

In this investigation, the experimental work finds its importance when it is necessary to study factors that are very complex to attain by theory.

The material type used in this investigation is aluminum alloy of AA 7075 which is used in most application because of their characteristics such as very high strength and special high toughness [8]. The chemical composition of this alloy is listed in table (1). The tensile test properties are listed in table (2).

Table (1): Experimental chemical composition of AA7075 alloy.

Elements	%Si	%Fe	%Cu	%Mn	%Mg	%Cr	%Zn	%Al
Content	0.018	0.05	1.7	0.013	2.65	0.216	5.5	Rem

Table (2): Mechanical properties of AA7075 alloy.

Ultimate strength MPa	Yield strength MPa (0.2% offset)	Elongation %	BH Hardness
585	508	11	160

The specimens; which are made from aluminum alloy (AA7075); are machined using a CNC machine. The specimens were manufacturing in a cylindrical shape (cantilever rotating bending), with smooth surface to satisfy the requirement and specifications of fatigue machine [9]. The cylindrical specimens dimensions were a tip diameter of (8 mm), a fixed diameter of (12 mm) and the overall specimen length of (146 mm) where the length of the fixed part of (40 mm), as shown in figure (1).

The testing machine of fatigue shown in figure (2) was designed with a constant amplitude-applying load (fully reversed bending). A small electrical heater was hold to the testing machine with a digital thermal control unit board, and the space test can be closed by isolated walls to keep the heat without leakage.

The highest temperature of 225 oC was chosen according to the maximum temperature on a piston rod that could be reached during the operation of the engine [10].

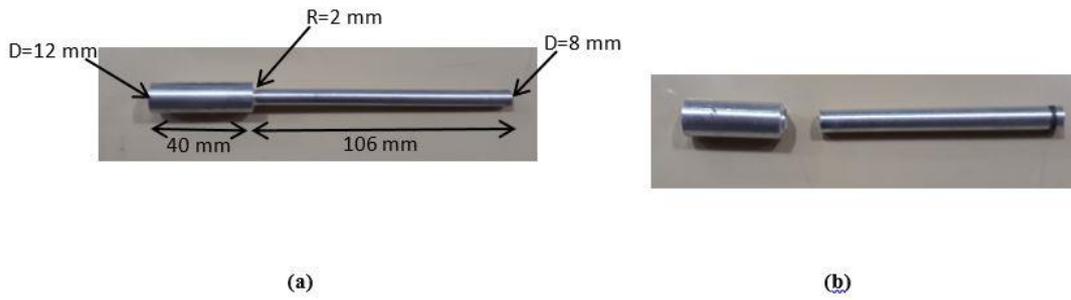


Figure (1): Fatigue specimen (a) before fracture and (b) after fracture.



Figure (2): Fatigue testing machine.

The calculated bending moment with the load and the lever arm is [11]:

$$M = F \cdot L \quad (1)$$

By using the section modulus of the specimen, it can be calculated the alternating stress amplitude as:

$$\sigma_f = \frac{M}{S} \quad (2)$$

$$S = \frac{\pi d^3}{32} \quad (3)$$

$$\sigma_f = \frac{32F \cdot a}{\pi d^3} \quad (4)$$

$$\sigma_f \approx 2F \quad (5)$$

Where

σ_f : Maximum alternating stress (MPa)

F : Applied load (N)

L : Bending arm = 106 mm

d : Diameter of the specimen = 8 mm

M : Bending moment (N.mm)

S : Section modulus of the specimen

Series of tests were conducted by acting a specimen to a stress cycling, and then the specimen life (number of cycles to failure) was counted at variable temperature of testing space. The fatigue test procedure is repeated to the other, specimens at progressively decreasing the applied stress amplitude, and the results that recorded are displayed graphically in the form of S-N curves

3- Results and Discussion

Fatigue tests were accomplished to determine the temperature effect on the aluminum alloy. Specimens were subjected to cyclic fully reversed loading with controlled external heat source. The maximum fatigue ranged from 240 to 540 MPa was used to test the samples at different temperatures (25 to 225 oC). Table (3) lists the experimental results of bending fatigue load at different level of the testing temperatures, where the specimen life was taken from the average value of three repeated tests.

Table (3): Experiment fatigue stresses with life of specimens at different temperatures.

σ_f (MPa)	Life \pm SD* (Cycles)				
	Temperatures °C				
	25	75	125	175	225
540	3576 \pm 603	2654 \pm 541	2046 \pm 389	737 \pm 121	98 \pm 18
480	8195 \pm 1027	5753 \pm 782	4317 \pm 563	2954 \pm 384	869 \pm 74
420	22120 \pm 1923	17405 \pm 1423	12572 \pm 1302	9638 \pm 939	2168 \pm 329
360	64965 \pm 3638	58080 \pm 3645	38279 \pm 3841	27803 \pm 2076	22803 \pm 1328
300	275935 \pm 12834	241625 \pm 7834	164561 \pm 6239	125469 \pm 6732	42999 \pm 4727
240	1793040 \pm 26039	1431171 \pm 23237	1257592 \pm 21834	976054 \pm 16340	675554 \pm 14383

* SD: Standard Deviation

The Basquin's equation is a power law regression and can be given by [12]:

$$\sigma_f = a * N_f^b \quad (6)$$

Where σ_f is the fatigue strength (MPa), N_f is the number of cycles to failure, a is the fatigue strength coefficient and b is the Basquin's exponent. The power law equation is expressing the fatigue behavior of the materials and its coefficient of determination (R2) [13].

It can be compared the results of fatigue test with the experimental results obtained by Reference [14] for aluminum alloy AA 7075 at room temperature (25 oC), to validate the results of this study, this comparison is shown in figure (3).

The Basquin's equations of fatigue data obtained from curve fitting of the results of figure (3) are expressed in table (4). Good agreement has been obtained when comparing the two expressions of Basquin's equations with a difference no more than 4.5% in fatigue strength coefficient and 3.4% in Basquin's exponent.

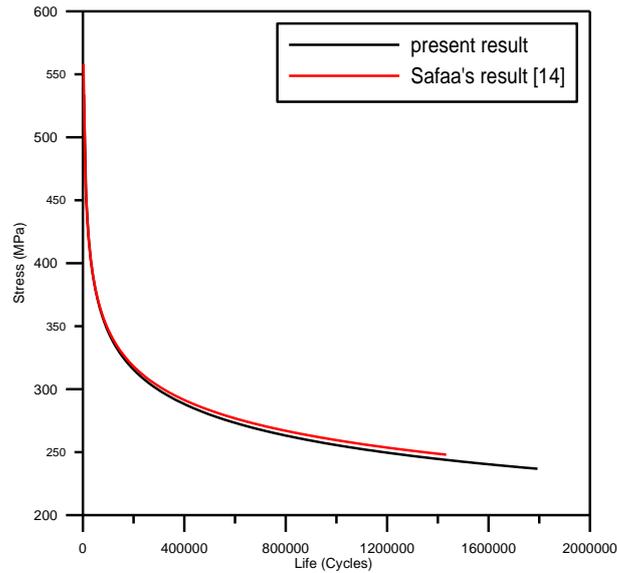


Fig. (3) A comparison between present results with Safaa's results [14].

Table (4): Basquin's equations comparison for present study with available fatigue data at room temperature.

Current result	$\sigma_f = 1558(N_f)^{-0.1308}$
Safaa's result [14]	$\sigma_f = 1488(N_f)^{-0.1264}$

The stress-life curves can be obtained from table (3), for the aluminum alloy AA 7075 at different temperatures.

Figure (4) shows the stress-life curves of aluminum alloy AA7075 at various temperatures. It is clear that increasing the temperature during fatigue test of the aluminum specimen leads to decrease its fatigue life. This behavior is resulted from increasing the plastic strain or deformation at lower stress level.

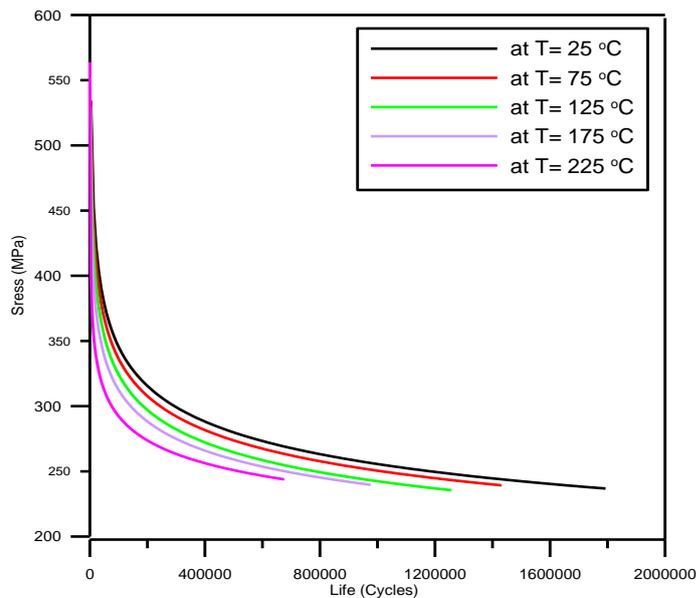


Fig. (4): Stress life curves fitting of experimental results at different temperature.

From the experimental data, the fatigue strength is related with the number of cycles to failure according to Basquin's equation at each testing temperature with different applied load. Therefore, the fatigue strength can be represented at each temperature as expressed in table (5).

Table (5): Basquin's equation at different temperature for Aluminum alloy AA 7075.

No.	Temperature	Basquin's equation	R ²
1	25 °C	$\sigma_f = 1558(N_f)^{-0.1308}$	0.9986
2	75 °C	$\sigma_f = 1465(N_f)^{-0.1278}$	0.9995
3	125 °C	$\sigma_f = 1386(N_f)^{-0.1262}$	0.9972
4	175 °C	$\sigma_f = 1192(N_f)^{-0.1163}$	0.9961
5	225 °C	$\sigma_f = 871(N_f)^{-0.0948}$	0.9742

From table (5), it is noted that these equations have coefficient of determination (R²) very close to unity, which indicated that the experimental data are closed to the fitted regression line. Also, this table confirms the decreasing of fatigue strength for aluminum alloy with increasing in testing temperatures. This behavior of fatigue can be attributed to the near-surface compressive residual stresses created from finishing machine processes, and this enhanced the fatigue performance due to strain hardening increasing of metallic materials at ambient temperature (25 oC). While at elevated temperature, these compressive residual stresses were relaxed and the strength of material would be weaker.

The Basquin's equation at elevated temperatures can be expressed by [10]:

$$\sigma_f = a * N_f^b * T^c \quad (7)$$

Where T is the absolute value of testing temperature measured in kelvin and c is represented the temperature sensitivity parameter.

In the similar trend, the determining of the fatigue behavior at different levels of temperatures (25, 75, 125, 175 and 225 oC) for aluminum alloy AA 7075 was obtained by using Statistical Package for the Social Sciences (SPSS) software (Version 25) to predict a mathematical expression from the experimental fatigue results as:

$$\sigma_f = 1558.21 * (N_f)^{-0.1308} * T^c \quad (8)$$

Where

$$c = 0.54564 - 0.004503 * T + 1.24567 * 10^{-5} * T^2 - 1.170266 * 10^{-8} * T^3 \quad (9)$$

This expression (equation (8)) can be given an alternative approach due to the complexity of most commercial finite element analysis simulation software to perform the fatigue analysis at elevated temperatures. In addition to that, there is a difficulty, costing and time consuming of the experimental tests.

To check the accuracy of equation (8), the results obtained from this equation are compared with the experimental data listed in table (3) for two values of exposed temperatures, i.e. 25 oC and 225 oC as shown in figure (5). The maximum absolute discrepancy between the real experimental data and the mathematical expression of equation (8) are 6.4% and 13.4% at testing temperatures of 25 oC and 225 oC, respectively.

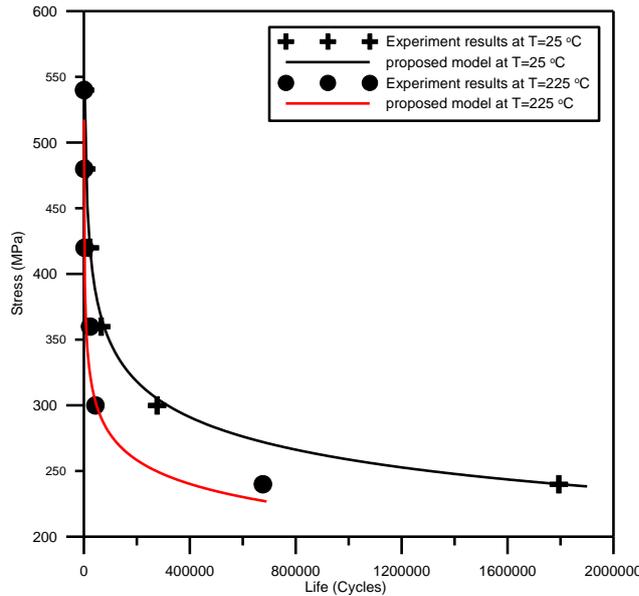


Fig. (5) A comparison between proposed model results with experimental data.

It observed that, the number of cycles was decreased with increasing the testing temperature at constant of the applied load; therefore, it is important to determine the percentage reduction in the fatigue life. The Fatigue Life Reduction Factor (FLRF) can be calculated from the following equation for each testing temperature relative to the room temperature [11]

$$FLRF\% = \frac{|\log N_{f_{RT}} - \log N_{f_T}|}{\log N_{f_{RT}}} * 100 \tag{10}$$

Where: $N_{f_{RT}}$ is the number of cycles to failure at ambient temperature (25 °C), and N_{f_T} is the number of cycles to failure at testing temperature.

Table (6) presents the percentage FLRF for aluminum alloy AA 7075 at different testing loads and temperatures, where these results calculated with respect to table (3).

It is shown that the maximum FLRF is (43.963%) occurred at temperature of 225 °C relative to room temperature when applying (540 MPa). Moreover, it can be observed from this table that the FLRF% increases with increasing in testing temperature.

Table (6): The Percentage Fatigue Life Reduction Factor (FLRF %) of aluminum alloy.

σ_f (MPa)	FLRF%			
	Temperature °C			
	75	125	175	225
540	3.644	6.824	19.304	43.963
480	3.926	7.113	11.323	24.901
420	2.396	5.648	8.304	23.217
360	1.011	4.773	7.658	9.448
300	1.059	4.126	6.291	14.839
240	1.565	2.463	4.223	6.779

4- Conclusions

In this paper, an experimental test was conducted to determine the temperature effect on the fatigue behavior of aluminum alloy AA 7075. The fatigue life at elevated temperatures was significantly affected. Comparing the fatigue results of present study with experiment data of another study at ambient temperature (25 °C), showed good agreement between them. The large decline in a number of cycles to failure limits the use of aluminum alloy at elevated temperatures. The modified Basquin's equation at different temperatures (proposed model) can be used as a good alternative

approach with maximum absolute discrepancy between the real experimental data and the proposed model are 6.4% and 13.4% at testing temperatures of 25 °C and 225 °C, respectively.

On the other hand, FLRF is increased with increased of the testing temperature to maximum value of (43.963%) occurred at a temperature of 225 °C relative to the room temperature with applied stress be equal to 540 MPa.

CONFLICT OF INTERESTS.

There are no conflicts of interest.

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تأثير درجة الحرارة المرتفعة على سلوك الكلال لسبيكة الالمنيوم AA 7075

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الخلاصة

يوضح هذا البحث تأثير عمر الكلال لسبيكة الألومنيوم (AA 7075)، وبظروف التحميل المستمر ذات القمة الثابتة، مع زيادة درجة الحرارة. إن التنبؤ لعمر الكلال لعينات الالمنيوم المتعرضه للاحمال الديناميكية باستخدام الطرق التجريبية التقليدية يجعل تحليل سلوك الكلال حقيقياً ويعطي نتائج دقيقة. كذلك تم تمثيل منحنيات الإجهاد-عدد دورات الفشل للعينات عند درجات حرارة مختلفة (25، 75، 125، 175 و 225 درجة مئوية). تمت مناقشة نتائج عمر الكلال عند درجة الحرارة الغرفة وعند درجات الحرارة المرتفعة من خلال علاقة باسكوين، وتم الحصول على انخفاض في عدد دورات الفشل للعينات المستخدمه عند زيادة درجة حرارة الاختبار. كذلك حصلت هذه الدراسة على توافق جيد عند مقارنة نتائج الدراسة الحالية مع نتائج تجريبية مستحصلة من دراسات أخرى. كما أشتق نموذج عام (تعبير رياضي) لحساب عمر الكلال لسبيكة الألومنيوم (AA 7075) عند درجات حرارة مختلفة. يمكن استخدام هذا النموذج الرياضي المقترح الذي تم الحصول عليه في هذه الدراسة لتقليل تكلفة ووقت الطرق التجريبية لمعرفة سلوك الكلال لسبيكة الالمنيوم. كما انه وجد زيادة في معامل تقليل عمر الكلال (FLRF) مع زيادة في درجة حرارة الاختبار وكانت اعلى زيادة لانتجاوز (43.963 %) وذلك في درجة حرارة 225 درجة مئوية نسبة الى درجة حرارة الغرفة عندما كانت قيمة الاجهاد المسلط تعادل (540 ميجا باسكال).

الكلمات الداله: - سبيكة الالمنيوم، الكلال، درجة الحرارة العالية، معادلة باسكوين.