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Experimental Study on the Effect of Temperature on the Fatigue Endurance Limit of Two AL Alloys

Dr. Sa'ad Abbas Al-Saraf
Ministry of Education/ Baghdad
Email:drsaad_alsaraf@yahoo.com

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ABSTRACT

In this work , an experimental study to obtain the fatigue endurance limit for two aluminum alloy , 2024 and 5052 , were carried out at stress ratio R=-1 and rotary bending tests . The fatigue tests were performed at RT, 100 °C, 200 °C and 300 °C in order to establish the S–N curve equations. The fatigue endurance limits for both alloys at different temperature conditions were calculated at 10^7 cycles from the empirical S-N curve equations. It was found that the fatigue endurance limit decrease with increasing the temperature. Also the reduction percentage in fatigue endurance limit for 5052 Al. alloy was higher than that of 2024 Al. alloy.

Keywords: Aluminum alloys, fatigue endurance limit, temperature.

دراسة عملية لبيان تأثير درجة الحرارة على حد الكلال لسبيكتين من الالمنيوم

الخلاصة

في هذا العمل و تم اجراء دراسة عملية لسبيكتين من الالمنيوم هما 2024 ، 5052 لاستخراج حد الكلال عند نسبة اجهاد R=-1 وفحوصات الانحناء الدوار. فحوصات الكلال تم انجازها عند درجة حرارة الغرفة و 100 °C و 200 °C و 300 °C لغرض استخراج معلدلات منحنيات العمر (S-N). حدود الكلال لكلا السبيكتين عند حالات اختلاف درجات الحرارة تم حسابها عند 10^7 دورة من المعادلات العملية المستخرجة . تم التوصل الى ان حد الكلال يقل عند زيادة درجة الحرارة . وان التخفيض في حد الكلال لنسبة مئوية لسبيكة 5052 كانت اعلى من سبيكة 2024 .

INTRODUCTION

It is a common sense that temperature causes a reduction in fatigue properties as well as in tensile properties, e.g. fatigue limit an tensile strength decrease with temperature [1]. Collins study observed in a gray cast iron that the fatigue strength keeps relatively constant for testing temperature ranging from 20 °C to 250 °C. Then there is an increase on fatigue strength for temperature around 350 °C to 450 °C and a decrease for temperature higher than 450 °C [2]. Collins also observed that the tensile strength follows the same tendency of fatigue strength. Shigley et al [3] proposed that the fatigue limit should be related to tensile strength evolution with temperature. They observed in most of the materials both fatigue limit and ultimate tensile stress have the same trend with temperature [3]. Also Shigley et al [3] proposed an equation to estimate the fatigue limit based on the ultimate tensile strength as follows:

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2412-0758/University of Technology-Iraq, Baghdad, Iraq

$$\sigma_{u(\text{test temp.})} = KT\sigma_{u(RT)} \quad \text{……………..} (1)$$

Where $\sigma_{u(\text{test temp.})}$ is the ultimate tensile strength at test temperature.

K_T is the temperature factor , and

$\sigma_{u(RT)}$ is the ultimate tensile strength at room temperature.

And

$$\sigma_{F.L\,(TT)} = \sigma_{F.L\,(RT)}\, K_T * k \quad \text{……………..} (2)$$

Where $\sigma_{F.L\,(TT)}$ is the fatigue limit at the test temperature.

$\sigma_{F.L\,(RT)}$ is the fatigue limit at the room temperature.

and **K** is the factor which takes into consideration all the other factors[1].

A method to predict the fatigue limit by using Vickers hardness measurement was proposed by Casagrande et al [4]. Fatigue limits for four kinds of steel in different metallurgical state (annealed, quenched and quenched – tempered) were estimated in two different ways, and the obtained values were compared to the experimental ones> A good correlation between Vickers hardness and the fatigue limits estimated by direct plastic deformation zone [4].

In the past years many empirical correlations among ultimate tensile, hardness and fatigue limit have been proposed, for example, the fatigue limit stress

$$\sigma_{F.L} = \frac{\sigma_u}{2} \quad \text{………} (3)$$

and

$$\sigma_{F.L} = 1.6HV \pm 0.1HV \quad \text{……………..} (4)$$

Where:

$\sigma_{F.L}$**:** is in MPa and HV in the Vickers hardness in Kgf/mm^2[5].

A more detailed investigation in the relationship between HV and fatigue limit was proposed by Murakami [6] as:

$$\sigma_{F.L.} = \frac{1.43\,(HV+120)}{(\sqrt{area})^{\frac{1}{6}}} \quad \text{…….} \ \mathbf{(5)}$$

Where:

$(\sqrt{area})$ is the square root of the projected area of defects. The aim of this study is to evaluate the fatigue endurance limits at different temperatures 100, 200 and 300^{o}C for two aluminum alloys under bending testing and stress ratio R= -1.

EXPERIMENTAL PROCEDURE

Materials

Materials used in this investigation were aluminum alloys; they are 2024 and 5052 alloys. The 2024 alloy (duralumin) being partially the first heat-treatable alloy and still used for wide application for many engineering and aircraft structural purposes in the form of forgings, extrude bar. This alloy has higher strength and lower corrosion resistance due to high copper content. 5052 aluminum αλλοψ provides good resistance to stress corrosion and has good welding characteristics [7].

CHEMICAL COMPOSITIONS

Table (1) illustrates the chemical composition of the aluminum alloys in wt%

Table (1): Experimental chemical composition of 2024 and 5052 Al alloys

Material	**Chemical composition**							
	Cu	Mg	Mn	Zn	Si	Fe	Ni	Al
2024	4	0.244	0.43	0.43	0.12	0.28	0.1	Rem.
5052	0.024	2.351	0.015	0.019	0.132	0.308	-	Rem.

TENSILE TEST

The tensile test was done using instron 225 testing machine that has a maximum capacity of 150 KN. These specimens have been taken from the received round bar of diameter Φ=16. Shape and dimensions of test specimens were taken according to German engineering standard (DIN 50123). The obtained results are shown in table (2).

Table (2) : Mechanical properties of the two Al alloys

Al alloy	**σ_u(MPa)**	**σ_y(MPa)**	**E(GPa)**	**G(GPa)**	**μ**	**Elongation %**	**HB**
2024	508	355	73	29	0.25	16	118
5052	195	102	71	28	0.27	14	48

The above results are an average of three readings.

FATIGUE ROTATING BENDING SPECIMENS

All fatigue specimens were manufactured using programmable CNC lathing machine by writing a suitable program from the profile of specimen on an edge of metallic plate. Then all the specimens were machined, corresponding to that profile by copy machining. During manufacturing of the specimens, careful control was taken into consideration to produce a good surface finish and to minimize residual stresses. The fatigue specimen is shown in figure (1).

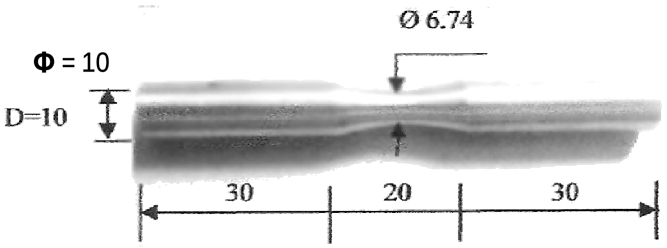

Figure (1) geometry of fatigue creep interaction specimens; dimensions in millimeter according to (DIN 50113) used standard specification

FATIGUE TEST RIG

A fatigue-testing machine of type PUNN rotating bending was used to execute all fatigue tests with constant and variable amplitude loading under room and elevated temperatures. The test rig is illustrated in fig. (2).

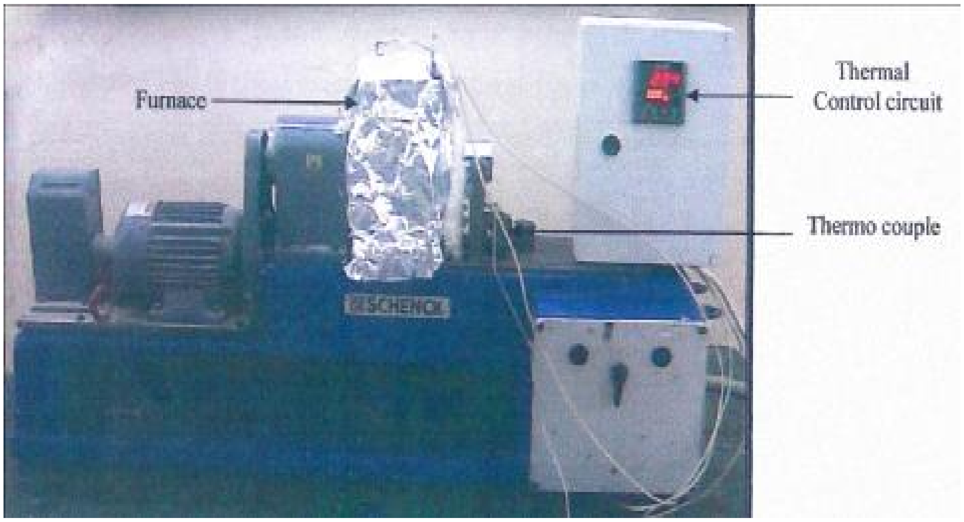

Figure (2): PUNN Rotary Fatigue Bending machine

The furnace making to raise the temperature of specimens to a known elevated temperature and the electrical control circuit can be found in Ref. [8].

EXPERIMENTAL RESULTS

12 fatigue specimens were tested for each alloy to investigate the basic S-N curves as shown in table (3).

Table (3): basic S-N results for the two alloys used

2024 alloy			**5052 alloy**		
Specimen No.	Applied stress σ_f(MPa)	N_f , cycles	Specimen No.	Applied stress σ_f(MPa)	N_f , cycles
1,2,3	300	2450,2800,1900	13,14,15	90	82000,87000,91000
4,5,6	250	44600,48600,50800	16,17,18	80	115000,104000,101000
7,8,9	200	162800,157800,151200	19,20,21	70	407000,398600,386000
10,11,12	150	288900,292600,307000	22,23,24	60	782000,807000,718600

8 fatigue specimen were selected to test for each alloy under 100°C, 200°C and 300°C to obtain the S-N curves at elevated temperatures. These results are given in table (4),(5) and (6) respectively.

Table (4): S-N curve results at 100°C

2024 alloy			**5052 alloy**		
Specimen No.	Applied stress σ_f(MPa)	N_f , cycles	Specimen No.	Applied stress σ_f(MPa)	N_f , cycles
25,26	300	1800,2000	33,34	90	70600,69200
27,28	250	31600,35200	35,36	80	101600,94800
29,30	200	133600,148000	37,38	70	332600,316400
31,32	150	201600,199600	39,40	60	610800,622900

Table (5): S-N curve results at 200°C

2024 alloy			**5052 alloy**		
Specimen No.	Applied stress σ_f(MPa)	N_f , cycles	Specimen No.	Applied stress σ_f(MPa)	N_f , cycles
41.42	300	800,600	49,50	90	50200,44600
43,44	250	20600,19800	51,52	80	77800,80200
45,46	200	101200,91600	53,54	70	201600,199800
47,48	150	162600,157000	55,56	60	310800,302000

Table (6): S-N curve results at 300°C

2024 alloy			**5052 alloy**		
Specimen No.	Applied stress σ_f(MPa)	N_f , cycles	Specimen No.	Applied stress σ_f(MPa)	N_f , cycles
57,58	300	160,200	65,66	90	18600,19100
59,60	250	11500,10000	67,68	80	31800,22800
61,62	200	35000,37000	69,70	70	102600,98800
63,64	150	90600,70800	71,72	60	170800,154100

DISCUSSIONS

Introduction

All the fatigue S-N curves of the two metals (2024,5052 Al alloys) under RT and elevated temperatures can be analyzed based on Basquin equation form as follows:

$$\sigma_f = A N_f^{\alpha} \qquad \text{………. (6)}$$

Where σ_f is the applied stress at failure

N_f is the number of cycles at failure due to the applied stress σ_f

A and α are material constants that can be evaluated by linearizing the curve by re-writing equation (6) in logarithmic form as following:

$$\alpha = \frac{h\sum_{i=1}^{h}\log\sigma_f \log N_f - \sum_{i=1}^{h}\log\sigma_f \sum_{i}^{h}\log N_f}{h\sum_{i=1}^{h}(\log N_f)^2 - [\sum_{i=1}^{h}\log N_f]^2} \qquad \text{…… (7)}$$

And

$$\log A = \frac{\sum_{i}^{h}\log\sigma_f - \alpha \sum_{i=1}^{h}\log N_f}{h} \qquad \text{……… (8)}$$

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

And h is the total number of readings

S-N curve equation under RT and elevated temperatures

Table (7) give the S-N curve equations for different conditions

Table (7): Basquin equations for two Al alloys used

2024 Al alloy	**RT**	$\sigma_f = 845\, N_f^{-0.126}$
	100°C	$\sigma_f = 827\, N_f^{-0.127}$
	200°C	$\sigma_f = 652\, N_f^{-0.119}$
	300°C	$\sigma_f = 524\, N_f^{-0.109}$
5052 Al alloy	RT	$\sigma_f = 560\, N_f^{-0.163}$
	100°C	$\sigma_f = 601\, N_f^{-0.172}$
	200°C	$\sigma_f = 791\, N_f^{-0.202}$
	300°C	$\sigma_f = 425\, N_f^{-0.176}$

Figure (3) shows the behavior of 2024 Al alloy while fig.(4) illustrates the fatigue behavior of 5052 Al alloy under RT and elevated temperatures.

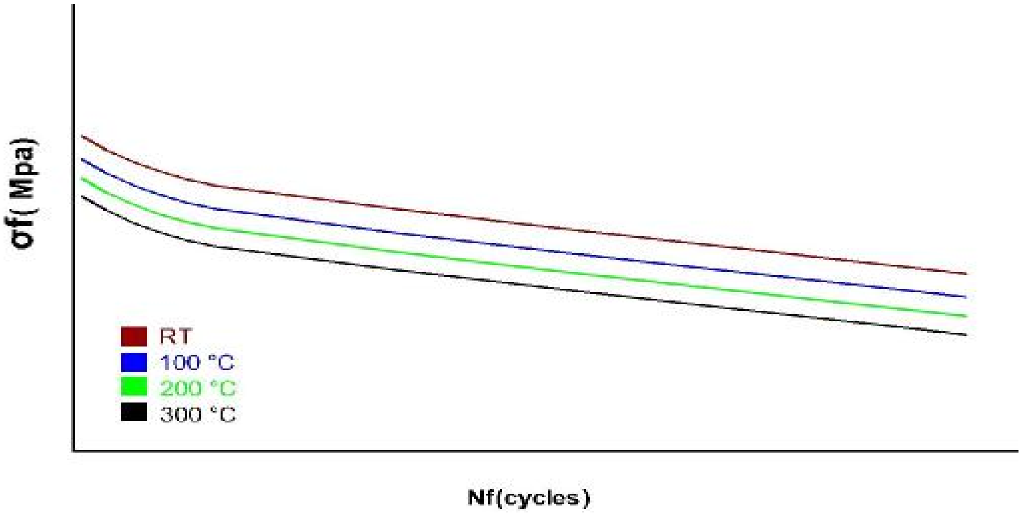

Figure (3) S-N curves at different temperatures for 2024 Al alloy

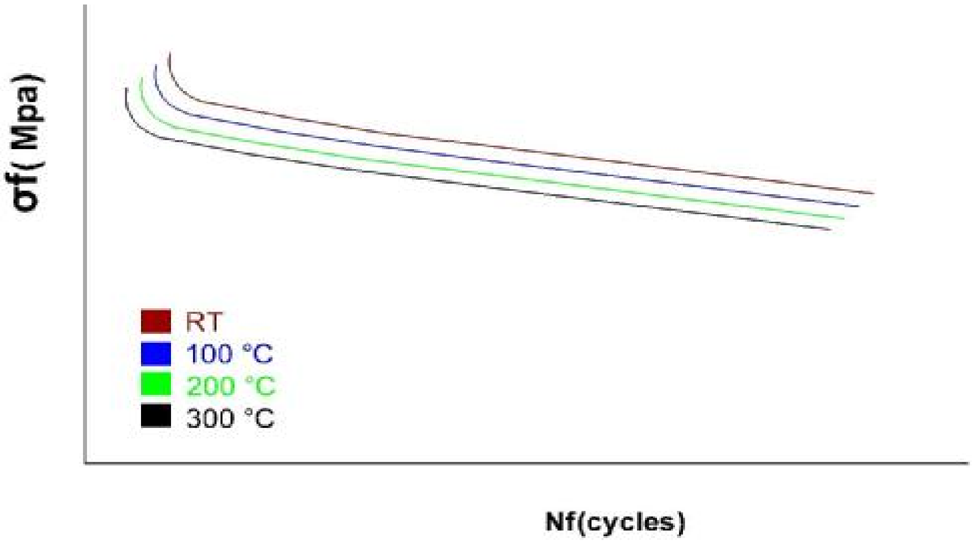

Figure (4) S-N curves at different temperatures for 5052 Al alloy

The S-N curves for both alloys at 100°C is a slightly different properly compared with the RT curves and the S-N curves behavior for 200°C shows a shift to right i.e the fatigue life decreases compared to the RT for both alloys. The reasons of the decrease in fatigue life with temperature could be related with the tensile properties of the material [9] or the formation of early surface cracks which in terms causes a rapid crack growth [10]. Another reason is the weak grains boundaries at high temperatures. As the high grain weaken, the transgranuler type propagation of cracks changed into intergranuler form [10]. The above results are in good agreement with the finding of Ref.[11].

FATIGUE ENDURANCE LIMIT AT DIFFERENT TEMPERATURE CONDITIONS

Table (8) gives the experimental fatigue endurance limit at different conditions.

Table(8) Fatigue endurance limits at 10^7 cycles for different temperature conditions

2024 Al alloy				**5052 Al alloy**			
RT	100°C	200°C	300°C	RT	100°C	200°C	300°C
111	107	96	89	41	37.5	28	25
Reduction % in endurance limit							
0	3.6	13.5	19.82	0	8.5	31.7	39

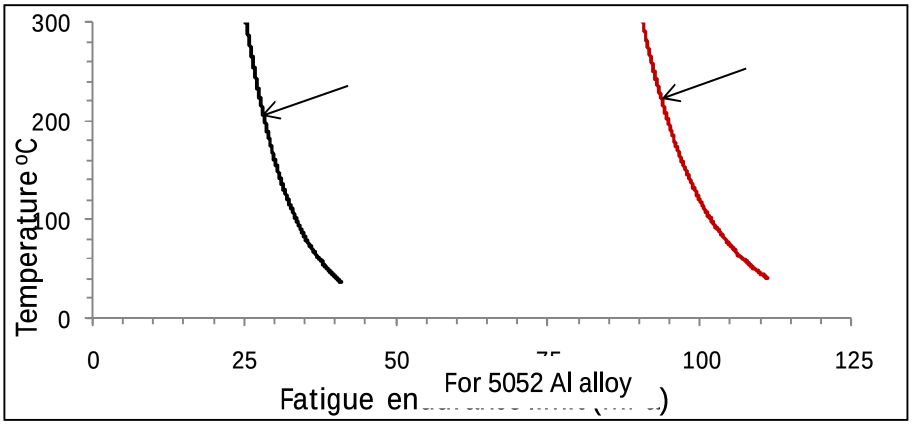

Figure (5) shows the variation of fatigue endurance limit with temperature

Figure.(5) fatigue endurance limit against temperature. The reduction percentage of the fatigue limit of aluminum alloys at elevated temperature is a result of averaging of the precipitation hardened material structure. The results of the fatigue limit of various materials as affected by temperature were collected by Forrest [8]. The reduction percentage of fatigue endurance limit of the two aluminum alloys used verses the temperature can be illustrated in fig.(6).

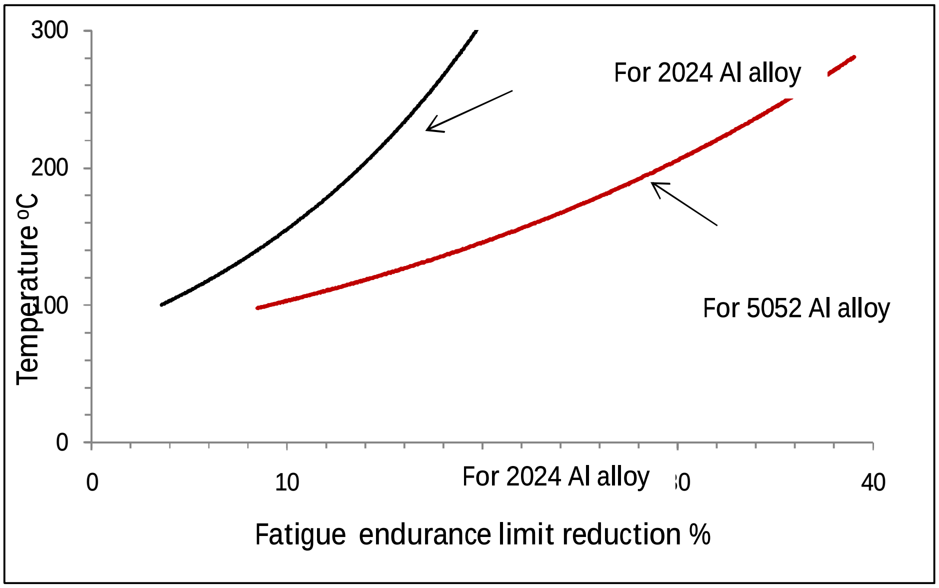

Figure (6) Reduction percentage in fatigue endurance limit against temperature

Figure(5) and (6) show a good correlation between the current experimental endurance limit data and the findings of Ref.[11]. The reduction percentage is higher in 5052 Al alloy that in 2024 Al alloy and the reason may be that high temperature embrittles the 5052 Al alloy. This embrittlement is due to superficial deformation of the specimens [12].

CONCLUSIONS

It can be concluded that:

1- The fatigue endurance limit for both aluminum alloys decreases with increasing the applied temperature.

2- The reduction percentage in fatigue endurance limit of 5052 Al alloy was higher than that of 2024 Al alloy.

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