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Investigation of Microstructure and Hardness Effects on Behavior of Aluminium Alloy under Creep – Fatigue Interaction

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ABSTRACT

In this work, an experimental study was carried out to obtain the fatigue damage for aluminum alloy, 2024-T4 under rotating bending loading and stress ratio R= -1. The experiments were done at RT(room temperature) ,25^{o}C ,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. The microstructure and hardness of aluminium alloy after fatigue-creep interaction testing have been investigated. Attention has been paid to the role of the microstructure and hardness on the fatigue-creep strength of aluminum alloy. It has been shown that, there is a little effect of microstructure in the cyclic response of aluminum alloy, while the hardness has a significant effect on the fatigue-creep strength. This is described numerically.

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Introduction

In recent years, there has been an increasing trend in the automotive industry to use 2024 aluminum alloy. The mechanical and physical properties of aluminum alloys such as 2024 and 6063 made them attractive for use in cost-effective, light weight engineering components. Kowfie and Chandler [1], proposed a stress-based fatigue model for correlating data and predicting fatigue life under loading conditions where cyclic creep occurs. This model is an extension of the Basquin stress-life relation .The model is tested on published creep-fatigue data of copper, steels, β-Ti alloy and agreement is found to be very good.

Microstructure analysis is used in failure analysis to determine the cause of failure. Failures can occur due to improper material selection and poor quality control. Microstructure analysis is used in research studies to determine the microstructure changes that occur as a result of varying parameters such as compositions, varying temperatures and processing steps. At high temperatures, mechanical components are frequently fractured by fatigue and creep [2].

The ratio of the total grain boundary surface area to material volume decreases with the decrease of specimen size and the increase of grain size. This leads to the decrease of grain boundary strengthening effect and the flow stress. The above explanation of size effect on flow stress is based on the conventional understanding of grain boundary strengthening behavior. Actually, there exists The above explanation of size effect on flow stress is based on the conventional understanding of grain boundary strengthening behavior. Actually, there exists size effect on the dislocation formation at grain interior.

In this work, a series of high temperature fatigue tests were carried out at 100, 200, and 300 ^{o}C to verify the microstructure and hardness effect on the fatigue life at different temperatures.

The effect of temperature on fatigue crack growth in P92 steel was studied by Byeong et. al. [2]. With temperature above 625^{o}C, crack growth rate increased and dimples were found, while at lower test temperatures, Striations and branch crackers were observed on the fracture surfaces. Also above 625^{o}C it was observed the Paris exponent (n) , $\frac{da}{dN} = Ak^{n}$, increase rapidly.

The thermo-mechanical fatigue tests were carried out in the condition where the value of complete strain and the temperature were under control. The material used was $X_{20}CrM_{o}V12.1$, $X_{10}CrM_{o}VNb9\text{-}1$(T/P91) and $X_{10}CrM_{o}VNb9\text{-}2$(T/P92) steels. The scope of temperature changes amounted to 450^{o}C, with the minimum temperature of 200^{o}C and maximum temperature of 650^{o}C. It was found that $X_{20}CrM_{o}V12.1$ steel shows lower life in comparison with the other steel used, by A.Marek et. al.[3].

Fatigue at elevated temperature is a damage process of the structural components produced by cyclic thermal loads. Under these loads a component can suffer unacceptable geometric deformation and change in its material properties. Cracks may appear in the component as a sequence of constraint and cyclic thermal loads [4].

Experimental tests were carried out in order to predicate the life of fatigue-creep interaction of copper alloy by Alalkawi et. al.[4] . it was found that the number of cycles to failure decreased with increasing temperatures and the fatigue strength was also decreased with temperatures according to a power law:

$$\sigma_{E.L} = 245T^{-0.215}$$

Where $\sigma_{E.L}$= endurance limit stress in (Mpa). T= temperature in (Celsius). The effect of microstructure on the cycle behavior and the substructure evolution of copper polycrystals have been investigated. The microstructure is described by a complex factor-grain size and texture combined. It is found that there is a very significant effect of microstructure in the cyclic response of copper at low and intermediate strain amplitudes by L.Llanes et. al.[5].

VAKILSINGH P. et al.[6] Studied the influence of test variables on the formation of the diamond grain configuration during high temperature creep and fatigue deformation of a wide variety of metals. They proposed mechanism for the formation of this interesting grain morphology and reviewed. It is concluded that the diamond grain configuration arises from a

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balance between grain-boundary sliding, grain-boundary mobility, interagranular deformation and defect imbalance across the grain boundaries and that it tends to be stabilized by intergranular cavitations. While the phenomenon occurs during high temperature fatigue in a variety of metals irrespective of their crystal structure, during creep it has been observed only in to h c p metals.

Materials and experimental procedure;

Experimental work

Material

The material is 2024-T_4 alloy, which is an aluminum copper alloy of widely industrial use such as airplanes, turbine blades and aerospace industries [7]. This alloy has good mechanical properties such as mechanical strength, light in weight and high in corrosion strength [2]. The character (T) represents thermally treated to produce stable tempers other than as fabricated alloy. The digit (4) represents how the alloy has been fabricated and it always followed by the symbol (T).

Chemical composition

Chemical composition of the alloy was analysis at (the specialized institute for engineering industries Baghdad-Iraq), using x-rays method. The results obtained, are compared with the American standards, and tabulated as shown in table (1).

Table 1. Experimental and standard chemical composition of 2024-T_4 Al. alloy, wt%

Material	Cu	Mn	Mg	Zn	Si	Fe	Ni	Al
2024-T_4 experimental	4.21	0.48	1.33	0.28	0.38	0.41	0.09	Rem.
2024-T_4 standard	4.4	0.6	1.5	0.25	0.5	0.5	-	Rem.

Mechanical properties

Tensile tests were carried out at RT(room temperature, 25°C) and at elevated temperature (200°C) in order to be used in the analysis of the cumulative fatigue-creep interaction.

Table 2. Mechanical properties of 2024 Al alloy

Condition of Property	σ_u(MPa)	σ_y(MPa)	E(GPa)	Ductility %	Hardness (HB)
Room Temp.(25°C)	515	361	77	19	121
Standard	472	325	73	20	120
200°C	332	207	52	23	89

The tensile tests was done using (Instron 225) testing machine which has a maximum capacity of 150KN. For creep and fatigue-creep tests, a small furnace was design and built to raise the temperature of the specimen to a known elevated temperature (200°C). Thus, an electrical furnace was made with suitable dimensions of (80*90*120 mm). The furnace can be attached to the testing machine, with a thermal control board as shown in Fig. (1)a.

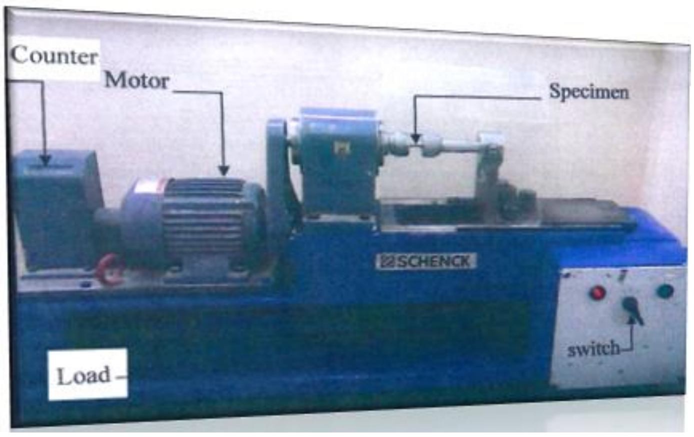


Fig. (2) a. the fatigue-creep testing machine

The mechanical properties of the alloy used can be illustrated in table (2).

Fatigue testing machine

Rotating bending fatigue tests were conducted at Room Temperature (25°C)and 200°C under stress ratio R=-1. This machine was used for creep, fatigue and fatigue-creep interaction tests. The test rig has a property of automatic cut-off when specimen fails. Fig. (2) a. Shows the fatigue-creep testing machine, which used in the ordinary tests at RT (25°C). While Fig. (2) b. shows the fatigue-creep testing machine, with designed furnace for testing specimens at 200°C.

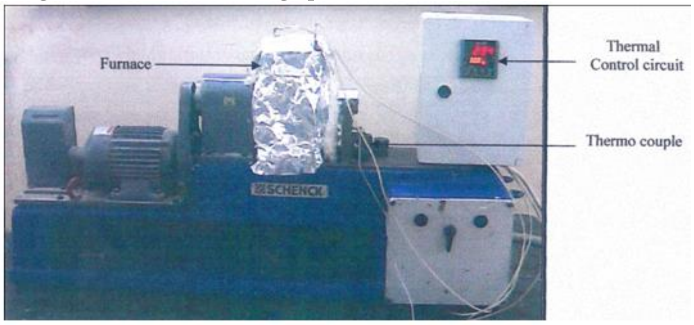


Fig. (2) b. the fatigue-creep testing machine with furnace

Fatigue-creep interaction specimen

Fig.(2)c. shows the shape and dimensions of fatigue-creep specimen. The manufactured specimens were classified into three groups as given in table (3).

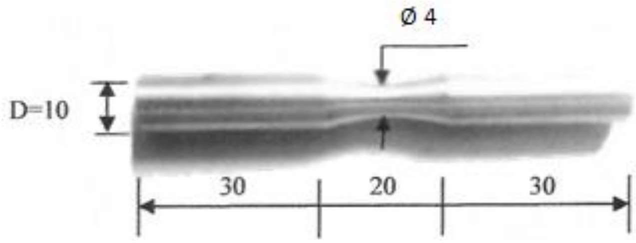


Fig.(2)c. The shape and dimensions of fatigue-creep specimen (All dimensions in mm)

Results and Discussion

S-N curve fatigue tests

Table (4) gives the results of 12 specimens subjected to applied load (F) and the bending moment (M) which can be calculated from

$$M = F * L \ldots\ldots\ldots\ldots \quad (4)$$

Where M in N.mm

L is the moment arm = 160 mm

The bending stress σ_b can be calculated from

$$\boldsymbol{\sigma_b = \frac{M_y}{I}} \ldots\ldots\ldots.(\mathbf{5})$$

Table 3. The plan of the experimental work

S-N curve fatigue tests	**12 specimens**
S-N curve fatigue-creep tests at 200°C	12 specimens
Cumulative fatigue-creep tests at 200°C	10 specimens

Table 4. S-N curve fatigue test results

Specimen No.	N_f cycles	Applied bending stress σ_b(MPa)	Average N_f cycles
1,2,3	16800, 19600, 20900	350	19100
4,5,6	305100, 288600, 266900	250	286867
7,8,9	1628251, 1086672, 1886625	225	1533178
10,11,12	4855682, 4226871, 4356525	200	4479693

Where y is the distance from the tip to the neutral axis of the mini-diameter of the specimen d, $r = \frac{d}{2}$ and d = 4 mm, $I = \frac{\pi d^4}{64}$ which is the second moment of inertia of the specimen. Thus, the bending stress (σ_b) was calculated from equation (6).

$$\sigma_b = 25.465\, F \ldots\ldots\ldots (6)$$

The application of equation (2) and (3) using the data of table (4), average data, can be seen in equations below and listed in table (5):

Where

$$\alpha = \frac{4*53.824-9.594*22.574}{4*130.595-509.585} = \frac{-1.278}{12.795} = -0.0999 \cong -0.1$$

And

$$\log A = \frac{9.594+0.1*22.574}{4} = 2.950$$

A= 892

Table 5. Shows the parameters of equations above

Log σ	Log Nf	Log σ lof N_f
2.544	4.281	10.890
2.397	5.457	13.082
2.352	6.185	14.548
2.301	6.651	15.304
Σ = 9.594	Σ = 22.574	Σ = 53.824

So equation (1) become

$\sigma_f = 892\ N_f^{-0.1}$

The behavior of 2024- T4 under constant fatigue stress amplitude and at RT (25°C)can be illustrated in Fig.(3).

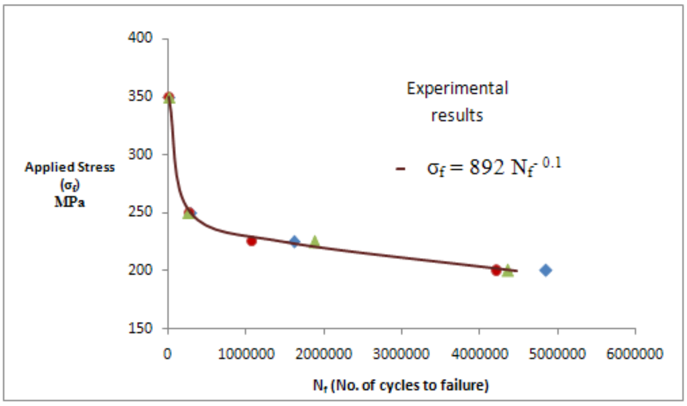


Fig.3. The S-N curve behavior under RT(25°C) condition.

S-N curve fatigue tests at 200°C

The same applied stresses were considered and the results are shown in table (6).

Table 6. Experimental fatigue S-N curve results at 200°C

Specimen No.	Life N_f cycles	Applied bending stress (MPa)	Average life
13,14,15	8800, 10600, 9000	350	9467
16, 17, 18	105600, 122800, 131500	250	119967
19,20,21	480600, 390800, 405600	225	425467
22,23,24	1200800, 1146000, 980800	200	1109200

The same procedure was used in calculating the material constants (A, α) as mentioned before and the results can be shown in Fig.(4).

Microstructure –test and grain size measurement

This study was undertaken to examine the effect of temperature, grain size and crystal structure of the material on the grain boundary configurationally changes during creep - fatigue deformation. Fracture surface were examined and interpreting the structures, so the specimens were grinding with many stages, and finally polished to be etched in the etching solution (etchant) (HF 5 % with alcohol),in order to measure the grain size for each specimen.

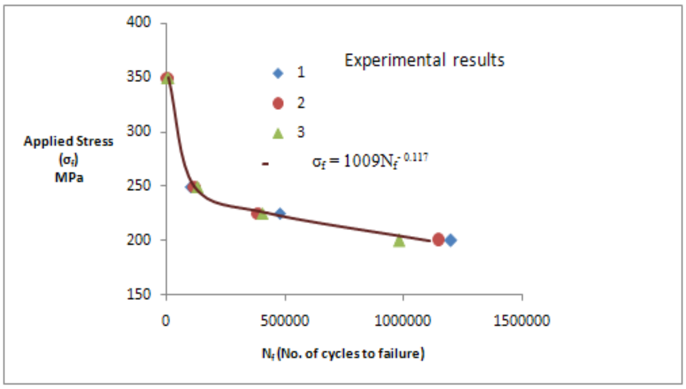


Fig. 4. The fatigue behavior of 2024-T_4 at 200°C

After getting the microstructure photo by using the electron microscope (MM300T Advanced Polarizing Darkfield Metallurgical Microscope), it is possible to find the average grain size by taking equal distance (2mm) and measure the no. of grains in different places of the prepared specimen and their results are given in table (7) below.

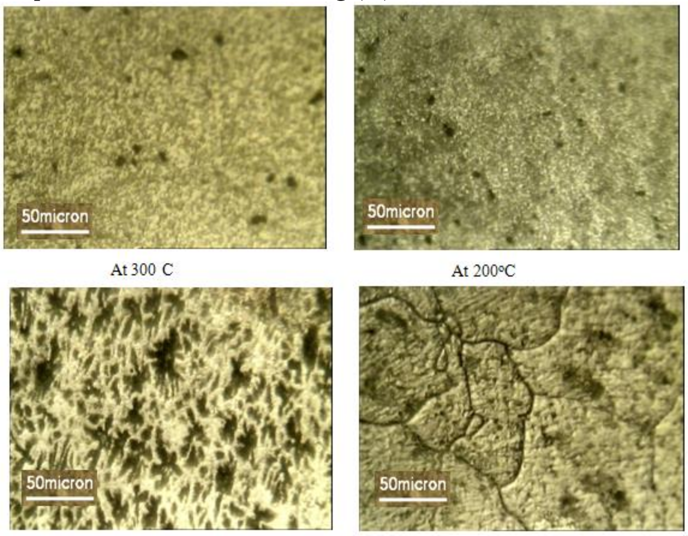
Table 7. Grain size measurements after testing the specimens under fatigue- creep interaction

Grain size (μm)			
Room temp.	100°C	200°C	300°C
13	11	9	8

Note that: (1) The magnification factor was x=400.

(2) The above results were an average of 10 readings.

The microstructures of the specimens crept at four temperatures and applied cyclic stresses were observed using a scanning electron microscope equipped with x-ray energy dispersive analyses. The microstructures of four conditions at different temperatures are illustrated in fig (5).



At 100oC At room temperature

Fig. 5. The microstructures of four conditions at different temperatures after testing at fatigue- Creep interaction

The shape of the grain is essentially the same as that of room temperature but in a distorted form. The distortion is best expressed in terms of the number and total length of grain boundaries oriented near 45° to the stress-axis on longitudinal sections. This conclusion is completely the same as in Ref.[6].

The variation of grain size (D) after thermal cyclic with temperature (T) can be described by the relation

$$T_{(C^o)} = 1 \times 10^7\, D^{-4.98} (\mu m) \quad \ldots\ldots\ldots\ldots\ldots (1)$$

It is clear that the microstructure of the specimen after thermal cyclic testing slightly affected when the temperature increased. .[10].

Hardness

The hardness test were carried out using the (HLN-11A,Time Group Inc.) under load (KN) at different location of the minimum diameter of the specimens. The results are tabulated in table (8). The variation of temperature with hardness can be illustrated in Fig. (6).

Table 8. Hardness under different temperatures

Hardness(HB)			
Room Temp.**	100°C	200°C	300°C
146	120	77	68

*The above data are the average of three readings.
** Room Temp. was measured and recorded (25°C).

While the relationship between T(°C) and hardness (HB) can be described by the equation.

$$T = 6.3 * 10^{7} HB^{-2.892} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(2)}$$

From Ref.[3], the relation between the endurance fatigue strength $\sigma_{E.L}$ at the same temperatures used in this work and the same material was obtained as follows

$$\sigma_{E.L.} = 254T^{-0.215} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(3)}$$

From equ. (2) and (3), the relation between fatigue-creep strength and HB hardness can be written as

$$\sigma_{E.L.} = 5.345\ H^{0.6217} \quad \ldots\ldots\ldots\ldots\ldots \text{(4)}$$

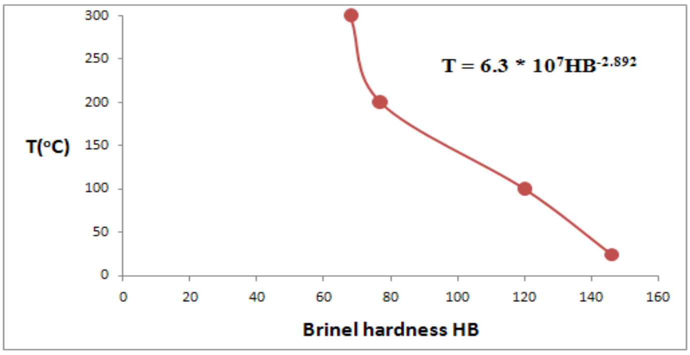


Fig. 6. shows the variation of temperature with the HB hardness of aluminium alloy

Applying the above equation for different temperatures the predicted hardness can be illustrated in table (9).

Table 9. Experimental and predicted hardness for the material used

Temp. °C	Endu limit σE.L.	HB Experimental	HB Predicted from equation (3)
Room temp.	116	146	141
100°C	112	120	133
200°C	88	77	90
300°C	63	68	53

The behavior of the aluminium alloy in terms of strength and HB hardness can be illustrated in Fig. (7).

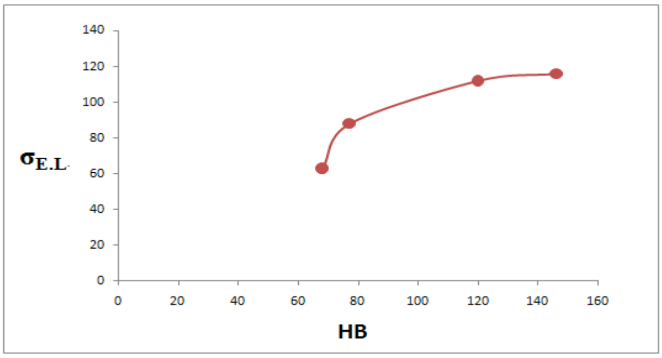


Fig. 7. Fatigue strength against HB at different temperatures (room temperature to 300°C)

Conclusions

1. The microstructure was slightly effect on the behavior of aluminum alloy.
2. The Brinell hardness of the aluminum alloy obtained from empirical analysis agreed to the experimental results within 10% difference.
3. Equations to predict Brinell hardness (HB) were proposed as a function of temperature and endurance limit stress.

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