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Cumulative Thermal Fatigue Damage for Aluminum Alloy under Variable Stresses

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Abstract. Thermal-Fatigue is the main reason for the failures of many components under high temperature and cylices loading. In this paper experimental tests were carried out in order to predate the life of thermal fatigue of aluminum alloy. Fatigue-temperature interaction have been performed on Aluminum alloy (6063-T6) under varying temperatures and stress ratio R=-1.It was founded that the number of cylices to be failed decrease with increasing temperatures and the fatigue strength was also decrease with temperatures according to a power law. In high temperature conditions, the service interaction between temperature and fatigue occurs and it cause significant reduction of the number of cyclic. It is founded that the reduction life ratio (N_f Evaluated temperate /N_f Room Temperature) increase when temperature raise.

Keywords: Thermal-Fatigue interaction, Aluminum alloy, Endurance limit, Thermal damage,

1. Introduction

At elevated temperatures creep and fatigue can act simultaneously to produce a concerted, harmful effect on a material. A material operating in high temperature conditions can experience both creep strains and cyclic strains that can seriously compromise the material's expected lifetime. For example, if a material experiences creep strains while undergoing fatigue cycling, its fatigue life can be greatly reduced [1]. Similarly, if a material experiences fatigue cycling while undergoing creep, its creep life can be significantly reduced. The combined effect of creep and fatigue can pose serious problems for those designing a system to perform for a defined lifetime. [1] There has been significant research into predicting the combined effects of creep and fatigue on materials in various operating conditions [2]. Studied The mean stress insensitivity factor may be determined from experimental data at fixed ratio of mean stress-to-stress amplitude, other than zero, or by trial-and-error method to fit experimental mean stress data onto the S–N curve due to zero mean stress. The model is tested on published creep–fatigue data of copper, steels and β- Ti-alloy and agreement is found to be very good [3]. A model for high temperature creep–fatigue lifetime of modified 9Cr–1Mo martensitic steels is proposed. This model is built on the basis of the physical mechanisms responsible for damage due to the interaction of creep, fatigue and oxidation. These observations led to the distinction of two main domains, corresponding to two distinct types of interaction between creep, fatigue and oxidation. As no intergranular creep damage can be observed in the tested loading range, the proposed modeling consists in the prediction of the number of cycles necessary for the initiation and the propagation of transgranular fatigue cracks.
A new life prediction method is developed taking the equivalent grain boundary cavity radius as a damage parameter. By [4] this method is applicable for stress controlled mode. It involves the effects of fatigue, static creep and cyclic creep during the fatigue–creep interaction. By employing this method, the fatigue–

creep life is assessed for 1.25Cr0.5Mo steel at 520 °C and 540 °C. The predicted lives are compared with the tested ones and a good agreement is found between them. Fatigue and creep tests were carried out on alloys aged to peak strength at 170 ºC by [5], The tensile properties of the alloys aged at 170 ºC increased in the order Al–4%Cu, Al–4%Cu–0.3%Mg, Al–4%Cu–0.3%Mg–0.4%Cd, and Al–4%Cu–0.3%Mg–0.4%Ag. Despite differences in their microstructures and tensile properties, the fatigue performance of the alloys was relatively unaffected. Fatigue behavior was similar in each case and the alloys showed identical fatigue limits. Major differences were observed in the creep performance of the alloys creep tested at 150 ºC in the peak strength condition age hardened at 170 ºC. Creep performance of the alloys increased in the order of their tensile properties [6]. Carried out an investigation on short crack growth behavior of type 316 stainless steel under creep-fatigue conditions at (550^{o}C) for high strain ranges of (0.9-2.5%) and 60 minutes hold time using a high temperature reverse bending rig. The analysis revealed the dominant failure characteristics to be the individual initiation and growth behavior of many minor cracks in Stage I, and their subsequent coalescence in Stage II. Increasing the strain range increases the number of minor cracks and promotes the process of minor crack coalescence. Predominantly inter granular long cracks are found to form under tensile stresses and trans granular the Langdon Symposium short cracks under compressive stresses [7]. This research investigates the effect of this interaction by studying the effect of constant amplitude fatigue (CAF) and creep separately, and then fatigue-creep interaction is introduced by testing the alloy under constant amplitude with some holding time periods through the test at high temperature (150^{o} C) to the aluminum alloy 2024 T4 may be subjected to an interaction of fatigue and creep effects at high temperature. The results showed that the life time of the alloy decreases due to fatigue-creep interaction as compared to creep alone in about 77%, and in about 80% as compared with fatigue alone. This is a result of accumulated fatigue damage superimposed on creep damage. Creep allows more free spaces for fatigue cracks paths that accelerate failure. A theoretical model to calculate the time to failure due to fatigue-creep interaction has been proposed [8]. Investigated the effects of process parameters on the creep-fatigue behavior of hot-work tool steel for aluminum extrusion die. Tests were performed on a Gleeble thermo mechanical simulator by heating the specimen using joule's effect and by applying cyclic loading up to 6.30 h or till specimen failure. Displacements during the tests at 380, 490, 540 and 580°C and under the average stresses of 400, 600 and 800 MPa were determined. A dwell time of 3 min was introduced during each of the tests to understand the creep behavior. The results showed that the test could indeed physically simulate the cyclic loading on the hollow die during extrusion and reveal all the mechanisms of creep-fatigue interaction [9]. This research detailed observations of fractured specimens of 9–12%Cr martensitic steels subjected to creep–fatigue loadings at 823 K were carried out. Observations revealed that oxidation phenomena strongly influence the creep–fatigue lifetime whereas no creep damage (cavities) can be observed in the present loading conditions. Two main interaction mechanisms between creep, fatigue and oxidation damage were highlighted. These two damage mechanisms correspond to two distinct domains of loading (expressed in terms of total strain range and holding period duration). Based on the identified mechanisms a creep– fatigue lifetime prediction model is proposed. The crack initiation is approached by the Tanaka and Mura model, whereas the crack propagation phase is accounted by the Tomkins formulation [10].

It is well known that the service life of structural components under dynamic loading conditions directly depends on the materials response to cyclic stress or deformation. In general, all engineering materials tend to alter their behavior in the presence of cyclic loads and temperatures. The main purpose of this research is to investigate systematically the fatigue behavior and the stability of near-surface for different temperatures and study the effect of temperature on the cumulative fatigue damage for aluminum alloy 6063-T6.

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2. Experimental Work

The material used in present study was Aluminum alloy (6063). The chemical composition of this alloy in weight percentage is given in table (1):

Table 1. Chemical composition of (6063) wt%

Elements	Fe	Mg	Si	Cr	Cu	Zn	Mn	Al
A6063	0.1-0.35	0.6-0.9	0.3-0.6	0.5	0.1	0.15	0.15	Balance
(Analyses test)	0.3	0.6	0.5	0.51	0.12	0.14	0.12	Rem

Hollow-glass cylindrical specimens with minimum diameter of (6.74) mm were used in the thermal fatigue test. The geometry of specimens is plotted in figure (1):

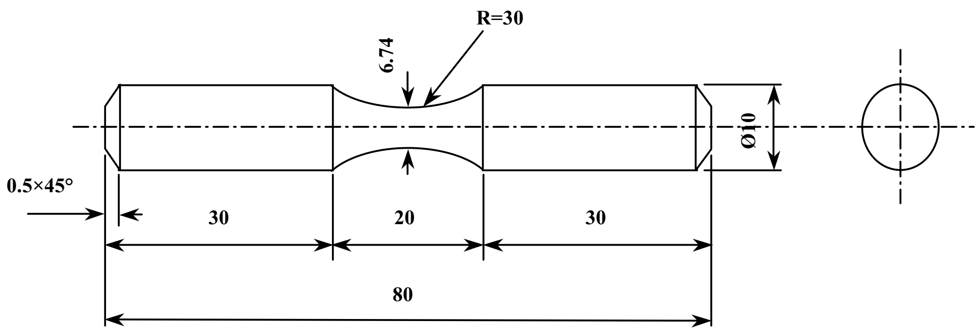

Figure 1. Geometry of thermal fatigue specimens; dimensions in millimeter according to (Din 50113) used standard specification

The mechanical properties of Al- alloy (T-6063) was achieved in materials engineering department/Faculty of engineering / Mustansiriyah University. The material used in this test is aluminum alloy (T-6063); from tensile test the mechanical properties of material are given in table (2):

Table 2. Mechanical properties of alloy (AL-6063-T6):

Property	Ultimate stress (Mpa)	Yield stress (Mpa)	Elongation%	Modules of elasticity (Gpa)	Hardness (HB)
Experimental	252	205	12	72	65
Standard	255	210	10	70	75

Roughness test: The results of the surface roughness are given in Table (3) where it is selected randomly: Table (3): surface roughness results of 5 specimens. The roughness was found to be equal to Ra=1µm average of 40 specimens).

Table 3. The results of the surface roughness

Specimen No.	**Average Roughness Ra (µm)**	**Peak Roughness Rt (µm)**
A1	0.5	1.2
A5	0.4	1.3
A10	0.35	1.1
A15	0.23	0.76
A20	0.17	0.7

3. Experimental Result

The test series of the experimental work were divided into two series (A, and B). Fatigue tests and thermal fatigue tests at constant stress amplitude are details in this section. Many specimens were investigated in this series; they were used to estimate the basic S-N Curve (fatigue only).

Series A: specimens were investigated in this series; they were used to estimate the basic S-N Curve (fatigue only). The results of this series are illustrated in table (4):

Table 4. Basic S-N Fatigue Results.

AA 6063-T6 S-N Dry Fatigue Data

Specimen No.	Stress level σ_f (MPa)	N_f cycle	Average	Condition
1, 2	200	4200, 4346	4272	Control
3, 4	175	0, 180002162	17100	Control
5, 6	150	82620, 75770	79195	Control
7, 8	125	411000, 456200	433600	Control
9, 10	100	3834442, 3460040	3647241	Control

Series B**:** This group is selected in order to investigate the fatigue at variable temperatures (low to high temperature i.e (Room temperature -150 °C). The result is shown in Table (5):

Table 5. Thermal Fatigue S-N Results.

AA 6063-T6 S-N Thermal Fatigue Data

Specimen No.	Stress level σ_f (MPa)	N_f cycle	Average	Condition
1, 2	200	3200, 3648	3424	At 150 °C
3, 4	175	14200, 12000	13100	At 150 °C
5, 6	150	42740, 40760	41750	At 150 °C
7, 8	125	338000, 356100	516050	At 150 °C
9, 10	100	1244430, 1690320	1467375	At 150 °C

Table 6. Fatigue parameters of (Al-6063-T6) at different temperate.

Temperature	A	m	S-N curve equation	$\sigma_{E.L.}$ (MPa)	Decrease in $\sigma_{E.L}$%.
At Room	476.586	-0.103105	$\sigma_f = 476.586 N_f^{-0.103105}$	90.449	
At 150 °C	480.778	-0.107349	$\sigma_f = 480.778 N_f^{-0.107349}$	85.212	5.23%

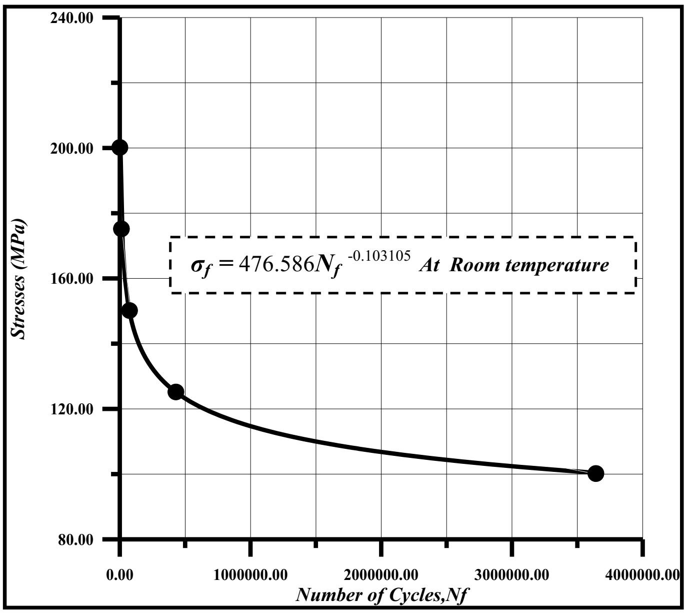

Figure 2. Normal *S-N* curve for 6063 Al alloy at room temperatur

4. Thermal Fatigue Damage Parameter:
Riedel (9) proposed creep-fatigue damage parameter D_{CF} which can be defined by:

$$D_{CF} = 2.9\left[\frac{\Delta\sigma^2}{2E}\right] + 2.4\left(1+\frac{3}{n}\right)^{1/2}\Delta\sigma\Delta\varepsilon\left[1+\left(\frac{\Delta\varepsilon_{cr}}{\Delta\varepsilon}\right)\right]1+\bar{n} \qquad (1)$$

Where n denoted the Norton exponent which determined in constant–stress creep exponent, $\bar{n}$ is the fatigue harding exponent that was calculated form the slope of the cyclic stress-strain curve.In the present study the D_{TMF} defined as:

$$D_{Thermal} = \frac{\sigma_{f\,150^{o}C}}{\sigma_{f\ Room}} \qquad (2)$$

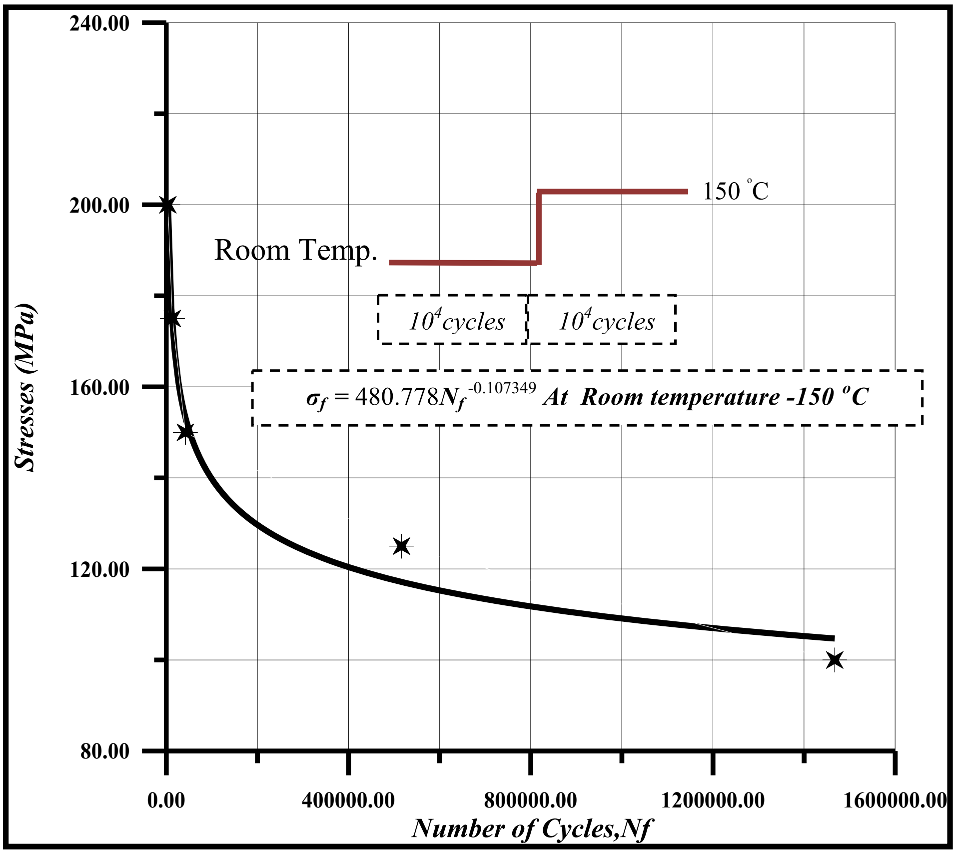

Figure 3. The *S-N* curve at low – high temperature variation

From table (4) and (5) the D_{TMF} can be obtained as illustrated in table (3).

Table 7. Thermo-Mechanical Fatigue Damage Results.

Cycles	**10^3**	**10^4**	**10^5**	**10^6**	**10^7**
$\sigma_{f\,Dry}$	233.790	184.383	145.417	114.686	90.449
$\sigma_{f\,TMF}$	229.032	178.874	139.701	109.106	85.212
D_{TMF}	0.979	0.970	0.960	0.951	0.942

High temperature effect is known to play an important role in the prediction of fatigue life of Aluminum alloy. At high temperature large plastic is accumulated to cause void formation .Hardet et al [10] proposed a life prediction approach which account for pure fatigue and environmental effects (temperature and oxidation effects) for the sake of simplicity a linear super poison law was applied:

$$\frac{da}{dN} = \frac{da}{dN}\Big|_{fatigue} + \frac{da}{dN}\Big|_{enviroment}$$

$$\left(\frac{N_f\, EvaluatedTemp.}{N_f\, RoomTemp} \right)$$

5. Thermal Fatigue Life Prediction:

At increasing temperature, from room temperature to 150 °C, the thermal tests fitting equation is In order to check the validity of the above equation cumulative thermal fatigue tests were carried out at low to high stress level with number of cycle 10^3 at each level and the results are tabulated in table (5). It is well known that the service life of structural components under dynamic loading conditions directly depends on the materials response to cyclic stress or deformation. In general, all engineering materials tend to alter their behavior in the presence of cyclic loads and temperatures. The results of this investigation demonstrate that the Aluminum alloy has exhibited accelerated fatigue behavior under the conditions of evaluated temperatures.

The reason of this observation is due to the damage generated by the high temperature testing activated damage micro mechanisms combine with fatigue damage and lead to drastic reduction in fatigue life. The obtained damage ratio and cyclic are plotted on figure (2) which shows that increasing the temperatures will increase the damage ratio and the cyclic ratio which in terms accelerates the fracture.

From table (7) observed that N_f is affect not only by the temperature ,but also the load sequences i.e that of (L-H) stress sequence loading at evaluated temperature, When the metal undergoes high temperature conditions, the thermal damage and fatigue damage cannot be treated separately in fracture failure. In high temperature conditions, the service interaction between temperature and fatigue occurs and it cause significant reduction of the number of cyclic. It is observed that the reduction life ratio increases when temperature raises as shown in table (8).

Table 8. Thermal Fatigue Test Results

Specimen No.	Applied stress (MPa) Low	Applied stress (MPa) High	$N_{f\,exp}$ *cycles*	Damage	$\frac{D_{Thermal}}{D_{Room}}$
A1	175	200	48000	0.77	1.28
A2	150	175	55000	0.76	1.18
A3	125	150	69000	0.75	1.20
A4	100	125	81000	0.74	1.216

6. Conclusion

The thermal-fatigue properties of Aluminum alloy (A-6063) are studied under rotating bending and range temperatures. Under fatigue, at elevated temperatures the life of components is reduced when the temperature is increased. The fatigue lives are longer in room temperature than at elevated temperatures for all test conditions. The fatigue damage (D_{exp}) resulted from the fatigue at elevated temperatures was greater than the experimental damage at room temperature. The increase in the damage ratio will increase in the cyclic ratio at different temperatures. The fatigue life is reduced by heating of 23% at 150^{o}C. Then the fatigue endurance limit is reduced by heating of 5.23 % at 150^{o}C .The effect of the thermal-fatigue should be consider in all design and application stage to present the early failure which may lead to extra cost in time and money. Finally the high temperature cases will faster the failure due to high percentages of damage accumulation.

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