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Thermomechanical Fatigue Damage Model for Life prediction of Navel Copper Alloy

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ABSTRACT.

TMF (thermomechanical fatigue) damage model devoted to prediction of the high temperature fatigue lifetime of navel copper alloy (C46400) , was proposed .This model was built on the basis of the stress –number of cycles curve responsible for damage due to interaction of high temperature and fatigue. This obtained prediction compared was very favorably with the cumulative experimental TMF results.

Keywords: navel copper alloy, thermomechanical - fatigue damage, life prediction.

1. INTRODUCTION.

Thermomechanical fatigue (TMF) is caused by combine thermal and mechanical loading where both the stresses and temperature vary with time. This type of loading can be more damaging by more than an order of magnitude compared with fatigue alone [1].

Thermomechanical fatigue is a complex subjected because of the interaction of several failure modes including fatigue, oxidation and creep with a wide variety of complex thermal and mechanical loads. For discussion it is convenient to consider damage from three primary sources; fatigue, oxidation and creep [2]. Damage from each process is assumed to obtain an estimate of the total fatigue life N_f [2].

$$\frac{1}{N_f} = \frac{1}{N_f^{fatigue}} + \frac{1}{N_f^{oxidation}} + \frac{1}{N_f^{creep}} \tag{1}$$

Alalkawi et. al.[3] studied fatigue-creep interaction of C3500 copper alloy under variable temperatures and stresses ratio R=-1 . They 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:

$$\sigma_{E.L} = 245T^{-0.215} \tag{2}$$

Viswamath R. et al.[4] proposed non linear finite element model to evaluate the multiaxial stress-strain behavior of Glidcop test specimens. The model consists of transient thermal analyses followed by elastic-plastic analyses that include a creep model. A good correction is observed between the predicted thermal fatigue life and experimental observation.

Thermal cyclic experiments have been performed in order to investigate the damage which can be generating by such treatment young modulus. It was found that young`s modulus is a good indicator to estimate fatigue damage under thermal cyclic [5].

Thermal fatigue in continuous carbon fiber epoxy matrix composite was investigated by Sboukai et. al. [6].

They used a resistively to monitor the thermal fatigue damage and they found that as resistivity decreased the thermal fatigue increased.

The thermomechanical behavior of passivity thin copper films was studied by Shen et. al.[7]. The thermal cycling spans a temperature range from (-196) to 600 ^{o}C. It was observed that the passivity film do not exhibit a significant stress relaxation at evaluated temperatures that is normally found in impassivity films. The behavior of C35600 copper alloy under elevated temperature and variable amplitude fatigue damage was investigated by Alalkawi et. al.[8]. They found that the life at elevated temperature is reduced when temperature is increased compared with the life at room temperature and damage ratio increases when the cyclic ratio is increased.

2. EXPERIMENTAL WORK.

The tested material was navel copper alloy (C46400). The alloy composition is given in **Table (1)**, The mechanical properties of material used in this study are given in **Table(2)**, Cylindrical hourglass-shape specimen that have (6.74) minimum diameter and 80 mm long were implemented. The length to diameter ratio was chosen so as to assure that specimens would not bend under compressive loading.

The fatigue test were carried out at room temperature and increasing temperatures with stress ratio R=-1. The shape and dimensions of specimen is illustrated in **fig. (1)**.

3. REVERSE BENDING RIG.

Fig. (2) shows the reverse bending test rig. The test specimens were clamped by two horizontal cross shafts using removable clamping plates. It was stressed in pure bending by rotation of the cross shaft about their axis. Both cross shafts were connected to cross beams by means of a pair of lever arms.

The drive for the rig was provided by a D.C. motor having a 6000 r.p.m. maximum speed. To prevent accidental damage to the machine in the case of a specimen Fracture, safety micro switch was set on one end of the cross shaft which would cut off the power supply and the rig. The specimen was heated by a horizontally mounted container (2kW) electric furnace. The furnace was made of stainless steel inlaid with insulating material to minimize heat loss. A thermocouple was fixed to the specimen to monitor continuously the temperature of the furnace. The thermocouple was connected to electrical circuit which can automatically monitor and maintain the set temperature. The difference between the thermocouple readings and the electric circuit was within _+ 3% °C. The same principals of the test rig can be found elsewhere [9].

4. RESULTS AND DISCUSSION.

Cyclic of metallic materials at high temperatures is known to cause a complex evolution of damage which can hardly be described in a unique, simple and straightforward manner. Such complex cycling may lead to damage contribution s from environment al degradation (usually termed oxidation, fatigue and creep). All the tests were conducted above the fatigue limit of this material (fatigue endurance at 10^7 cycles is equal to 155MPa) results of dry fatigue tests are summarized in**Table (3)**.

Regression of these test data in terms of the applied bending stress and cycles to failure gives the following power law equation:

$$\sigma_f = 805\ N_f^{-0.102} \qquad \text{At Room Temperature} \tag{3}$$

The results of increasing the temperature from room temperature to 300 °C with 9.0 °C/min heating rate, listed in **Table (4)**.

In same way, by using regression of the above data gives the following power law formula:

$$\sigma_f = 1050\ N_f^{-0.153} \tag{4}$$

The behavior of the material used in terms of the stress-life is shown in **fig. (3)**.

Chist et al [9] proposed creep- fatigue damage parameter D_{CF} which can be defined by:

$$D_{CF} = 2.9\left[\frac{\Delta\sigma^2}{2E}\right] + 2.4\left(1 + \frac{3}{n}\right)^{\frac{1}{2}} \Delta\sigma\Delta\varepsilon\left[1 + \left(\frac{\Delta\varepsilon_\sigma}{\Delta\varepsilon}\right)\right] 1 + \bar{n} \tag{5}$$

Where n denoted the Norton exponent which determined in constant – stress creep exponent, $\bar{n}$ is the fatigue harding exponent that was calculated from the slope of the cyclic stress-strain curve.

In the present study the D_{TMF} defined as:

$$D_{TMF} = \frac{\sigma_{f\,TMF}}{\sigma_{f\,Dry}} \tag{6}$$

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

The behavior of damage under high temperature can be illustrated in **fig. (4)**. High temperature effect is known to play an important role in the prediction of fatigue life of copper alloy. At high temperature large plastic is accumulated to cause void formation.

5. TMF LIFE PREDICTION.

At increasing temperature, from room temperature to 300°C, the TMF tests fitting equation is in order to check the vadility of the above equation cumulative TMF 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 (6)**.

Based on the above tests, the characteristics of TMF life was determined and it was found that the TMF results shown lower life compared with the fatigue test only. The previous results showed that the increasing temperature lead to a reduction of fatigue lifetime. However the environments were found to play a major role in TMF behavior of copper alloy. Several TMF damage laws have been proposed. The linear damage rule, the ductility exhaustion model [10] the strain range partitioning [11], the frequency modified fatigue life equations [12] are the typical creep- fatigue damage. This paper, however, employed a new technique based on the S-N equations. (Fatigue only and TMF S-N curves).

6. CONCLUSIONS.

1- Simple model for TMF damage was proposed for copper alloy which may be written as:

$$N_f = \left[\frac{1.29}{D_{TMF}}\right]^{20} \qquad (7)$$

2- A test technique for rotating bending TMF experiments has been developed and validated.

3- A special temperature sensor and electrical control circuit has been developed.

4- The TMF damage was evaluated based on S-N curves, where the fatigue damage was determined as the number of cycles to failure in TMF tests.

5- TMF lives predicted by D_{TMF} were compared to actual cumalutive lives that gave good comparison.

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8. NOMENCLA TURE.

$\sigma_{E.L}$: $Endurance\ limit\ stress\ (MPa)\ or\ fatigue\ strength$

T: $Temperature\,^{\circ}C$

N_f: $Number\ of\ cycles\ to\ failure, cycles$

σ_f: $stress\ at\ failure\ (MPa)$

D_{CF}: $Creep - fatigue\ damage\ parameter$

$\Delta\sigma$: $Stress\ range\ (MPa)$

$\Delta\epsilon$: $Strain\ range$

D_{TMF} : $Thermomechanical\ fatigue\ damage\ parameter$

Table (1): Chemical composition of copper alloy (C46400) wt%.

Property	Cu%	Sn%	Fe%	Pb%	Zn%
Standard	62	1.0	0.1	0.2	Rem.
Experimental	63	0.98	0.104	0.21	Rem.

Table (2): mechanical properties of copper alloy (C46400) .

Property	Yield stress (Mpa)	Ultimate stress (MPa)	Modulus of elasticity (Gpa)	Elongation %
Standard	186	414	112	22
Experimental	194	405	118	21

Table (3): Dry fatigue test results (three specimens for each stress level).

Stress (MPa)	Specimen No.	N\(cycles)
300	4,5,6	10000,9800,12000
275	1,2,3	66000,73000,61000
250	10,11,12	111000,133000,152000
230	7,8,9	300000,285000,262000
200	13,14,15	405000,411000,387000

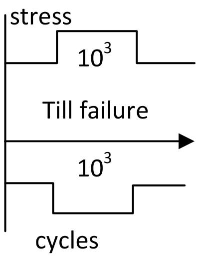
Table (4): Thermomechanical (TMF) fatigue test results (three specimens for each stress level).

Stress (MPa)	Specimen No.	N\(cycles)
300	16,17,18	3200,4000, 2600
250	19,20,21	14500,16000,12800
200	22,23,24	50000,52000,46000

Table (5): Thermomechanical fatigue damage (D_{TMF}) results.

Cycles	10^3	10^4	10^5	10^6	10^7
$\sigma_{f\ Dry}$	397.67	314.75	248.74	196.42	155.36
$\sigma_{f\ TMF}$	365	256.5	180.3	126.82	89.16
D_{TMF}	0.917	0.815	0.725	0.645	0.574

Table (6): TMF test results.

Specimen No.	Applied stress (MPa)		N_f cycles	D_{TMF}	N_f predicted (cycles)	Difference percentage %	Block stress
	Low	High					
1	200	300	18200	0.79	18166	0.186	
2	200	300	20400	0.786	19942	2.3	
3	175	250	30500	0.77	30054	1.46	
4	175	250	31600	0.7689	31145	1.44	

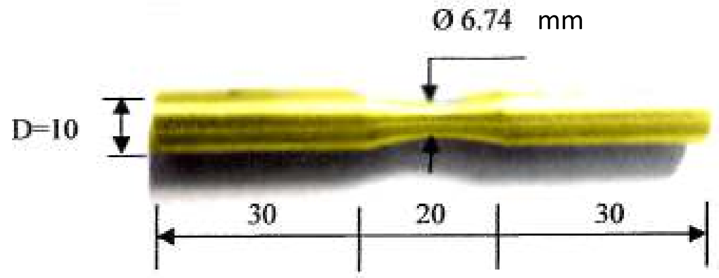


Figure (1): geometry of fatigue creep interaction specimens, dimensions. in millimeter according to (DIN 50113) used standard specification.

Figure (2): PUNN Rotary Fatigue Bending Machine.

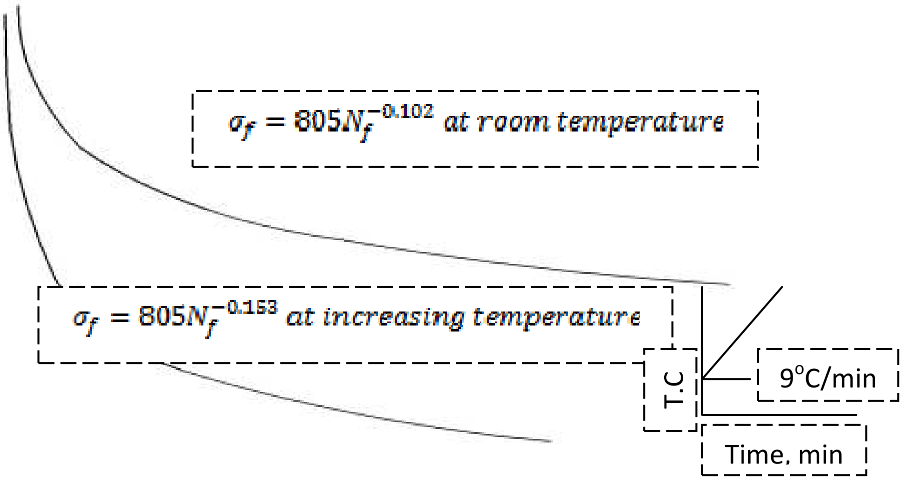


Figure (3): basic S-N curves for navel copper alloy at different temperature.

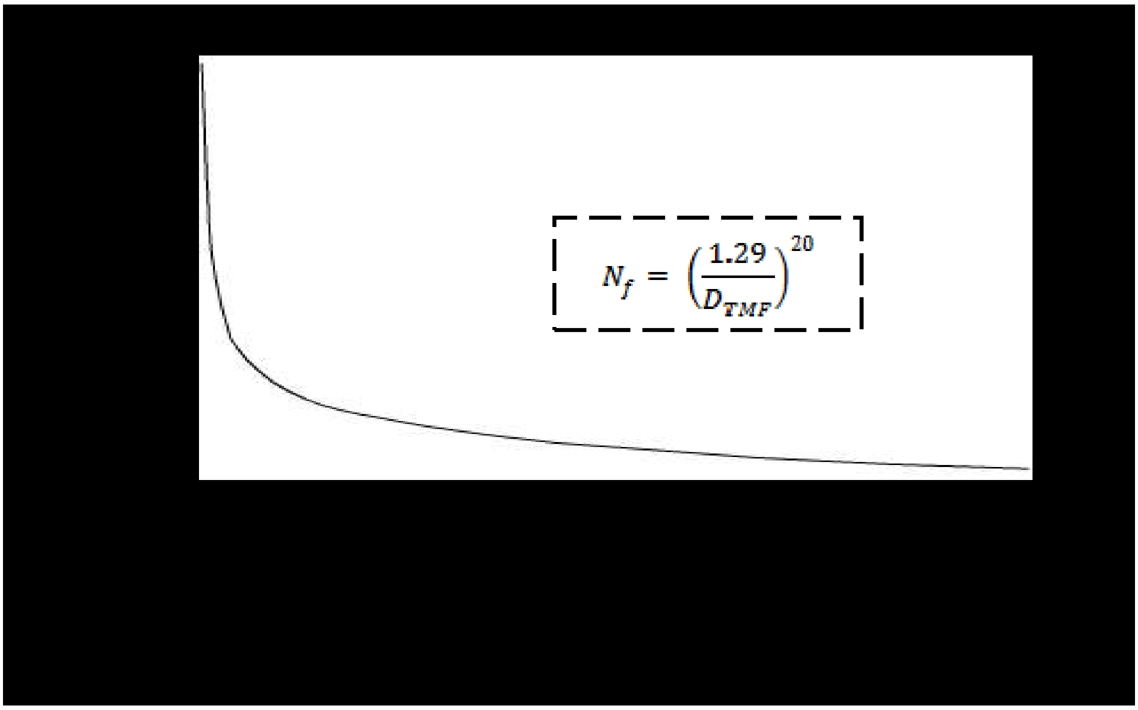


Figure (4): Thermomechanical fatigue damage (D_{TMF}) behavior.

نموذج لتخمين العمر للكلال الحراري الميكانيكي لسبيكة النحاس المستخدم في الملاحة

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الخلاصـــة.

تم اقتراح أنموذج للكلال الحراري الميكانيكي حيث خصص لتخمين أعمار الاجزاء التي تعمل تحت الكلال و درجة حرارة العالية لسبيكة النحاس المستخدم في الملاحة ذو الرمز (C46400) هذا الأنموذج بني على أساس منحنيات الاجهاد - عدد الدورات و التي بدورها تكون مسؤولة عن الضرر للتداخل بين درجات الحرارة العالية و الكلال و التخمينات المستخرجة من هذا الأنموذج اعطت توافق جيد مع النتائج العملية للكلال الحراري الميكانيكي المتراكم.

كلمات رئيسية : سبائك النحاس الملاحية ، التشوه بسبب الكلل الحراري الميكانيكي ، أعمار الأجزاء .