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

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Abstract

The microstructure and hardness of copper alloy after fatigue-creep interaction testing have been investigated. Experiments were carried out in the temperature range from room temperature to 300°C. Attention has been paid to the role of the microstructure and hardness on the fatigue-creep strength of copper alloy. It has been shown that, there is a little effect of microstructure in the cyclic response of copper alloy, while the hardness has a significant effect on the fatigue-creep strength. The relation between strength and hardness were described by the following equation:

$$\sigma_{E.L.} = 5.345\ H^{0.6217}$$

Keywords: Creep- fatigue interaction - microstructure – Hardness - copper alloy.

تأثير تداخل الزحف على الحار مع الكلال على التركيب المجهري و الصلادة لسبيكة النحاس

الخلاصة

تم مناقشة التركيب المجهري والصلادة, لسبيكة النحاس و ذلك بعد الفحوصات الخاصة بتداخل الكلال والزحف ولتجارب عملية انجزت بمدى من درجات الحرارة, ابتدأ من درجة حرارة الغرفة الى درجة 300 درجة مئوية. وقد تم التركيز في التوجيه لأظهار دور التركيب المجهري والصلادة على مقاومة السبيكة المعرضة لتداخل الكلال والزحف. وتم التوصل الى ان التركيب المجهري له تأثير بسيط مع الأستجابة الدورية لسبيكة النحاس, بينما الصلادة لها تأثير مهم على مقاومة السبيكة بعد فحصها بالتداخل للكلال مع الزحف وقد تم ايضاح ذلك بصيغة رياضية وكما في المعادلة ادناه بالأضافة الى الأختبارات العملية.

$$\sigma_{E.L.} = 5.345\ H^{0.621}$$

الكلمات المرشدة: الزحف, تداخل الكلال, التركيب المجهري, الصلادة, سبيكة النحاس

Introduction

Copper is an important engineering material since it is widely used in its pure state and also in alloys with other metals. In its pure state it is the most important material in the electrical industry. It has high electrical conductivity and corrosion resistance and is easy to fabricate. It has reasonable tensile strength, controllable annealing properties and general soldering and joining characteristics. Alloyed copper in the

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form of brass, and bronze is used extensively throughout mechanical engineering industry. Copper alloys do not have a sharply defined yield point, 50 yield strength is reported either as 0.5% extension under load, or as 0.2% offset. On the basis (0.5% extension), yield strength of annealed material is approximately one-third the tensile strength [1].

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 [1].

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.

Where:
a: surface crack length, µm
N: number of cycles, cycles
K: stress intensity factor $MPa\sqrt{m}$
A, n: material constants
$\sigma_{E.L}$**:** Endurance limit stress MPa
T: Temperature ^{o}C
D: grain size diameter, µm
HR: Rockwell Hardness
HB: Brinnle Hardness
P: Applied load (N)
d: minimum diameter of specimen (mm)
σ_b: Applied bending stress (MPa)

Fatigue at long lives was studied in materials of different sizes, Alpha brass, Copper and aluminum were tested in tension- compression at constant stress- amplitude over a life range of 10^{4}- 10^{7} cycles. Grain size, D, was varied by at least a factor of ten and beyond 10^{5} cycles had no effect on life in copper and aluminum. In brass, however an order of magnitude decrease in D increased life by about the same amount. [3].

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 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:

Specimen and test temperature

C35600, copper alloy was used in this study; table (1) shows the chemical composition of C35600 copper alloy. Specimens were prepared and tested according to DIN 50113 standard specifications. The thermo- mechanical fatigue test is one of the most complex and time-consuming mechanical tests, based on which the life of materials is determined. The tests were conducted under temperature and stress control. Test temperatures were, 25^{o}C (room temperature), 100^{o}C, 200^{o}C and 300^{o}C. Fig (1) shows the geometry of fatigue creep interaction specimens.

The tensile tests were done foe three specimens. The obtained results, average of three readings, with the standard values are shown in table (2).

Fatigue- creep interaction testing

A fatigue- testing machine of type PUNN rotating bending was used to execute all fatigue test with constant amplitude stress, as illustrated in Fig. (2)

The specimen is subjected to an applied load from the right side of the perpendicular to the axis of specimen, developing a bending moment. Therefore, the surface of the specimen is under tension and compression stress when it rotates. The value of the load (P) is measured by Newton (N) applied to the specimen for a known value of bending stress measured by (MPa) and extracted from applying the equation below.

$$\sigma\,(MPa) = \frac{32 * 125.7\,P\,(N)}{\pi\,d^3} \quad \dots\dots\dots \; (1)$$

Or

$$\sigma\,(MPa) = \frac{1281\,P(N)}{d^3(mm)^3} \quad \dots\dots\dots \; (2)$$

Where, the force arm is equal to 125.7 mm and d (mm) is the minimum diameter of the specimen [7].

For fatigue- creep interaction test, a small furnace is required to heat the temperature vacuum of the specimen to a known elevated temperature. Thus, an electrical furnace is made with suitable dimensions of (10* 12 *140)mm^3. The furnace can be attached to the unit board as shown in Fig. (3) [8].

Microstructure –test and grain size measurement

This study was carried out 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) ($FeCl_3$ 5 % with alcohol),in order to measure the grain size for each specimen.

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 number of grains in different places of the prepared specimen using the method of linear intercept. This method gives the average grain size diameter in the direction of crack growth [9].

The microstructure of the specimens for all the stages of this investigation were observed using a scanning electron microscope equipped with X-ray energy dispersive analysis according to the SEM KY kY-3800B. The microstructures of four conditions at different temperatures are illustrated in fig (4).

It is important to note that fig.(3)and table (3), increasing the temperature will made a fine grain size.[12].

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^{O} to the stress-axis on longitudinal sections [6].

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

$$T_{(C^{o})} = 1 \text{ X } 10^{7}\, D^{-4.98} (\mu m) \quad \ldots (3)$$

The above equation was obtained by applying the least square method to the data of the table (3). The least square method equation may be written by the form [8, 9].

$$\alpha = \frac{h\sum_{i=0}^{h}\log T \log D - \sum_{i=0}^{h}\log T \sum_{i=0}^{h}\log D}{h\sum(\log D)^2 - \left[\sum_{i=0}^{h}\log D\right]^2} \quad \ldots\ldots (4)$$

$$\log A = \frac{\sum_{i=0}^{h}\log T - \alpha\sum_{i=0}^{h}\log D}{h} \quad \ldots\ldots\ (5)$$

Where α and A material constants for the above equation, α = -4.98 and A = $1x10^{7}$, and h is the number of specimens used in testing. The above equation was used for building all the relations obtained in this work.

It is clear that the microstructure of the specimen after thermal cyclic testing slightly affected when the temperature increased. [10, 13].

Hardness

The hardness tests 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 (4). The variation of temperature with hardness can be illustrated in Fig. (4).

While the relationship between T(^{o}C) and hardness (HB) can be described by the equation.

$$\mathbf{T = 6.3 * 10^{7} HB^{-2.892}} \quad \ldots\ldots. (6)$$

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

$$\boldsymbol{\sigma_{E.L.} = 254T^{-0.215}} \quad \ldots.. (7)$$

From equ. (6) and (7), the relation between fatigue-creep strength and HB hardness can be written as

$$\boldsymbol{\sigma_{E.L.} = 5.345\, H^{0.6217}} \quad \ldots. (8)$$

Applying the above equation for different temperatures the predicted hardness can be illustrated in table (5).

The behavior of the copper alloy in terms of strength and HB hardness can be illustrated in Fig. (5).

The above behavior is in good agreement with Ref.[11].

Discussion

(1) A reliable lifetime prediction is particularly important in the design and optimization of complex loading components or structures such as gas turbines, nuclear plants and chemical plants. In complex loading conditions, fatigue and creep interaction behavior usually occurs at high temperatures under cyclic loading, which results in material damage and hence shortening of the component life [14].

(2) When the creep and fatigue operate simultaneously, therefore, it is necessary to consider not only the individual effects, but also effect of their interaction, to obtain a more accurate prediction of component life [15].

(3) Fatigue at long lives with creep interaction of copper alloy was studied under stress ratio R= -1. The effects of temperatures, which is described by three values 100, 200, 300 ^{o}C, on the microstructure have been investigated. It was found that, table (3) and equation (1), a slightly effect of temperature on the grain size and this finding is agreed well with Ref.[16].

(4) It should therefore be noted that the overall damage evolution is governed not only by the temperature, but also by reducing the hardness due to raising temperatures, leading to reduction in the endurance limit and fatigue-creep life [17].

Conclusions

1. As the temperature increases, the interaction between the processes of fatigue and creep can lead to significant reductions in hardness endurance limit and life.
2. No significant change in the grain size diameter when the temperature is increased.
3. The microstructure was slightly effect on the behavior of copper alloy.
4. The Brinell hardness of the copper alloy obtained from empirical analysis agreed to the experimental results within 10% difference.
5. Equations to predict Brinell hardness (HB) were proposed as a function of temperature and endurance limit stress.

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Table (1) shows the chemical composition of C35600 copper wt%

Elements	Cu	Zn	Pb	Fe	Other
Standard*	63	34	3.0	0.1	Rem
Experimental	63	33.6	3.1	0.15	Rem

*The above data are recorded according to B121/B1210M standard

Table (2) mechanical properties of material used

Property	Yield stress (Mpa)	Ultimate stress (MPa)	Elongation%	Modulus of elasticity (Gpa)	Hardness (HR)
Standard C35600 B121/B12101M	310	405	20	115	65
Experimental test	295	400	16	110	58

Table (3) Grain size measurements after testing the specimens under fatigue-creep interaction

Grain size (µm)			
Room temp.	$100^{O}C$	$200^{O}C$	$300^{O}C$
13	11	9	8

Note that: (1) The magnification factor was x=400.
(2) The above results were an average of 10 readings.

Table (4) Hardness under different temperatures

Hardness(HB)			
Room Temp.**	$100^{o}C$	$200^{o}C$	$300^{o}C$
146	120	77	68

*The above data are the average of three readings.
** Room Temp. was measured and recorded ($25^{o}C$).

Table (5) Experimental and predicted hardness for the material used

Temp. ^{o}C	Endurance limit* $\sigma_{E.L.}$(MPa)	HB Experimental	HB Predicted from equation(3)
Room temp.	116	146	141
$100^{o}C$	112	120	133
$200^{o}C$	88	77	90
$300^{o}C$	63	68	53

*From Ref. [4]

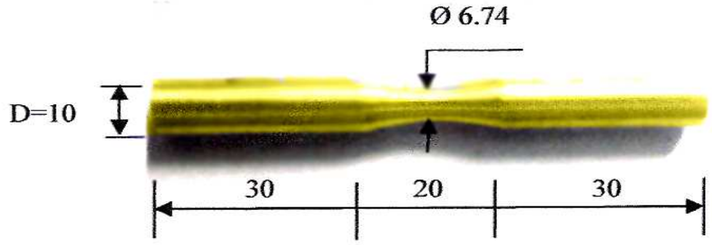


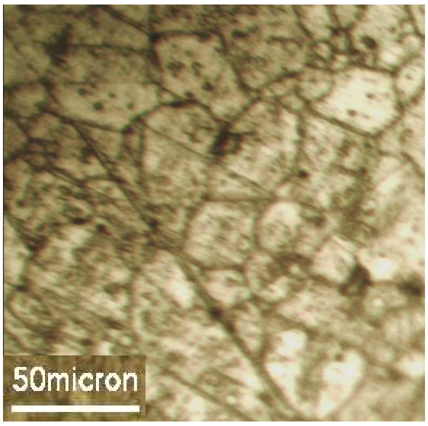
Figure (1) : shows the geometry of fatigue creep interaction specimens, dimensions in (mm)

Figure (2): PUNN Rotary Fatigue bending machine [8]

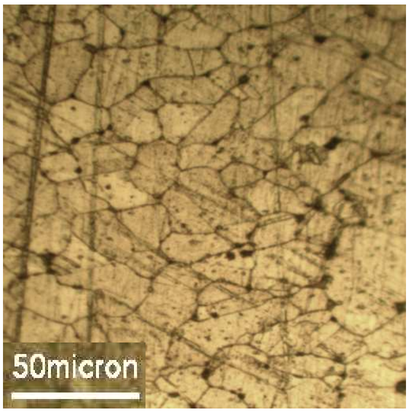
(a)

(b)**Figure**

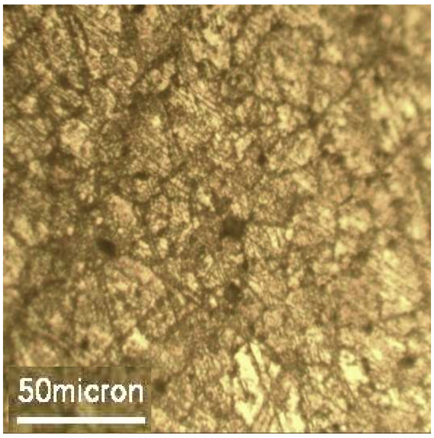
(3): (a) furnace attached with fatigue machine (b) ER-NA temperature controller [8]



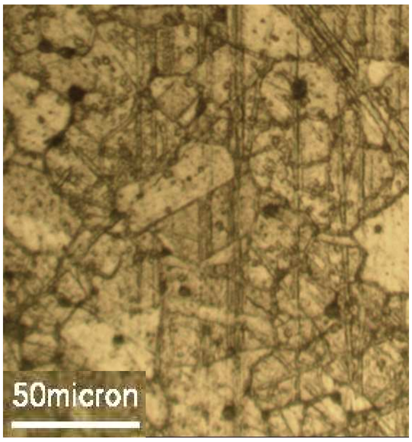
At room temperature (X400)



At 100^{o}C (X400)



At 200^{o}C (X400)



At 300^{o}C (X400)

Figure (4-A) The microstructures of four conditions at different temperatures after testing at fatigue- Creep interaction.

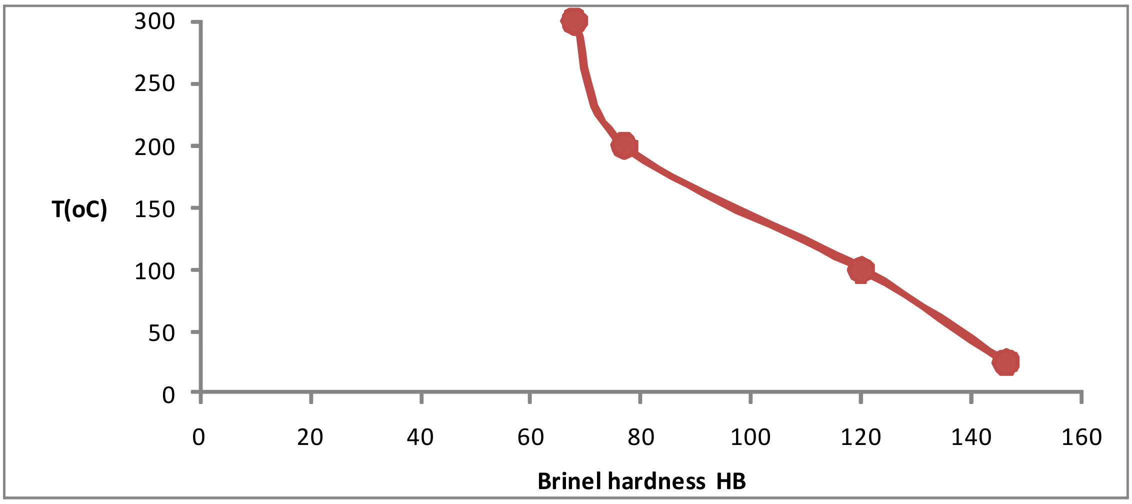


Figure (4-B) shows the variation of temperature with the HB hardness of copper alloy

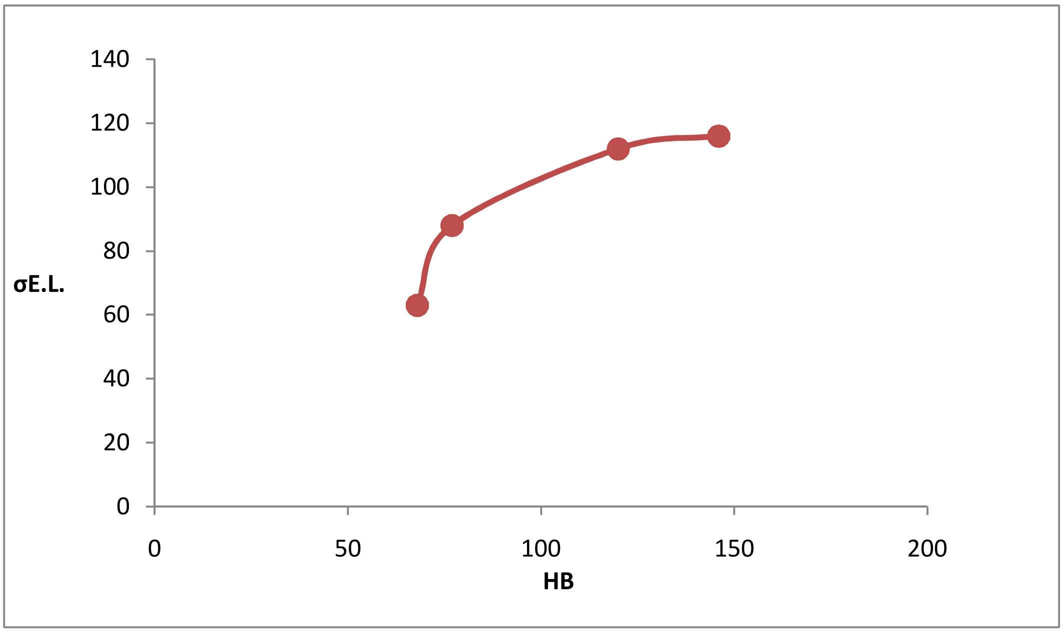


Figure (5) Fatigue strength against HB at different temperatures (room temperature to 300^{o}C)