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Temperature Dependence of High-Temperature Vacuum Tensile-Fatigue Life and Deformation in Cu-Al Alloy with 9 % Al*

By Shigeo MATSUSHIMA**

Tensile fatigue test of Cu-Al alloy (with 9 % Al) in vacuum at high temperature was performed by the high-temperature vacuum tensile-fatigue tester made to work at pressure 10^{-5} mmHg, up to 700 °C, under load of maximum 50 kg and with load frequency 1~10 sec⁻¹. And slip lines and fractured faces in fractured specimens were observed by optical microscope. The relationship between the present results and the results of tests on fatigue strength and high-temperature vacuum tensile-strength⁽⁸⁾ was discussed. The empirical formula for the relationship among the cyclic load w , the number $\bar{N}$ of load cycles to cause the fracture and testing temperature T (°K) can be given by

$$\bar{N} = \bar{N}_0 (w/W_0)^{-\bar{B}} \exp[-A'(T-T_0)^2],$$

where $A' = 0.88 \times 10^{-5} \text{°K}^{-2}$, $\bar{B} = 8$, $\bar{N}_0 = 4 \times 10^2$, $T_0 = 360 \text{°K}$ and $W_0 = 46.5 \text{ kg}$.

1. Introduction

Many fatigue tests⁽¹⁾ at high-temperature were performed. However fatigue tests in vacuum and tests at high temperature in vacuum were seldom performed: tests in vacuum were done by Gough et al.⁽²⁾ and Wadsworth et al.⁽³⁾ and ones at high temperature in vacuum by Danek et al.⁽⁴⁾, Stephens et al.⁽⁵⁾ and Takeuchi et al.⁽⁶⁾.

Therefore in the previous work⁽⁷⁾, a high-temperature vacuum tensile-fatigue tester made to work at pressure 10^{-5} mmHg, up to 700 °C, under load of maximum 50 kg and with load frequency 1~10 sec⁻¹ was produced by way of experiment, and fatigue test of Cu-Al alloy with 5 % Al was performed at high-temperature in vacuum.

Then in the present work, fatigue test of Cu-Al alloy with 9 % Al was performed at high-temperature in vacuum. Temperature dependences of fatigue life and fatigue deformation were studied, and slip lines in fractured specimens were observed. Moreover, the relation between present results and results of tensile test⁽⁸⁾ done at high temperature in vacuum was discussed, and expression of the empirical formula which describes the relationship among the temperature, fatigue life, cyclic load,

etc. was attempted.

2. Testing method

Cu (99.9 %) and Al (99.99 %) of prescribed amount were melted in a closed graphite crucible in which carbon powder covered up these metals. And their blocks 0.6×6×7 cm of Cu-Al alloy with 9 % Al were made. These blocks were cold-rolled to 20 % reduction, and were then annealed at 800 °C in furnace for 20 min and left there until cooled. By repeating this process, 0.30 mm sheets were prepared, from which specimens of shape and size shown in Fig. 1 were cut out, annealed in vacuum of 10^{-2} mmHg at 800 °C for 1 hour and cooled to room temperature at the rate shown in Fig. 2.

The mechanism and structure of the fatigue tester⁽⁷⁾ which can be evacuated to 10^{-5} mmHg and in which the specimen can be heated up to 700 °C under load of maximum 50 kg are shown schematically in Fig. 3.

In the test, the specimen first was brought to thermal equilibrium at a required temperature,

Fig. 1 Specimen (thickness 0.30 mm)

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** Lecturer, Department of Mechanical Engineering, the Defense Academy, Yokosuka.

and then the frequency of the cyclic load, which was pulsating pull and sinusoidal form, was controlled to 7 sec^{-1} . And the slip lines on fractured specimens were observed under microscope. Fig. 4 shows the temperature distribution of specimens during the state of no loading, measured with alumel-chromel thermojunction. From the figure we see that the temperature distribution of tested range was nearly uniform.

Fig. 2 Cooling curve of specimens in pressure 10^{-2} mmHg

Fig. 3 High-temperature vacuum tensile-fatigue tester

Fig. 4 Temperature distribution in testing range of specimen

3. Testing results

Relation between the cyclic load and deformation obtained from the test which was done under cyclic loads 6, 10, 16 and 20 kg at each testing temperature is shown in Figs. 5 and 6, from which we see that the breakdown deformation tends to increase with the increase of the temperature and cyclic load. And the deformation of the specimen tested at about 600°C is extremely lower: breakdown deformation of the specimen, which was tested under cyclic load 2 kg at 600°C and fractures at the number 1×10^{-3} of load cycles to fracture, is about 1.3 mm and is considerably lower than that tested at $400\sim 500^\circ\text{C}$ shown in Figs. 5 and 6.

Relation between the number $\bar{N}$ of load cycles to cause the fracture and testing temperature T , obtained by the test which was done under cyclic loads of certain constants, are shown in Fig. 7. From Figs. 5~7, we see that the number of load cycles to cause the fracture tends to increase with an increase of cyclic load and testing temperature. Moreover, from Fig. 7 we see that the larger the load or the lower the temperature, the lower becomes

Fig. 5 Deformation ϵ and the number N of load cycles to cause the fracture: under cyclic loads 6 and 10 kg

Fig. 6 Deformation ϵ and the number N of load cycles to cause the fracture: under cyclic loads 16 and 26 kg

$-(d \log_{10} \bar{N} / dT)$.

Relation between minimum deformation rate ($d\varepsilon/dN$), which is minimum value of deformation made from one cycle of cyclic load, as obtained in this test and the number $\bar{N}$ of load cycles to cause the fracture is shown in Fig. 8. In Fig. 8, the relation between ($d\varepsilon/dN$) and $\bar{N}$ can be expressed by

$$\left. \begin{aligned} \log_{10}(d\varepsilon/dN) &= -A \log_{10} \bar{N} + B \\ A &= 6/5, \quad B = 0.2 \end{aligned} \right\} \dots\dots\dots (1.1)$$

4. Slip lines on fractured specimens

Below the characteristic temperature at which

Fig. 7 The number $\bar{N}$ of load cycles to cause the fracture against testing temperature T

Fig. 8 Minimum deformation rate ($d\varepsilon/dN$) and the number $\bar{N}$ of load cycles to cause the fracture

breakdown deformation increases considerably, many slip lines are seen on fractured specimens near where the fracture occurred. They are found on longitudinal strips arising along the loaded direction and are short, as shown in Fig. 9. And according as it draws near the fractured position, the number of slip lines increases and some of double slip lines appear.

Above the characteristic temperature, long slip lines which constantly keep a space between the line and the nearest line appear as shown in Fig. 10. Below about 500 °C, the number of the slip lines increases with an increase of the testing temperature. However cracks at grain boundaries appear above about 400 °C, and the number and

Fig. 9 Specimen tested on conditions of cyclic load 26 kg, testing temperature 200 °C and the number 2.3×10^4 of load cycles to cause the fracture

Fig. 10 Specimen tested on condition of cyclic load 10 kg, testing temperature 400 °C, the number 9×10^3 of load cycles to cause the fracture

Fig. 11 Specimen tested on condition of cyclic load 2 kg, testing temperature 600 °C, the number 1×10^3 of load cycles to cause the fracture

size of those cracks increase with an increase of the temperature. And at about 600 °C, these slip lines rarely appear near the fractured position, and most of grain boundaries near that position change into cracks as shown in Fig. 11.

Below about 400 °C, fracture occurs along cleavage planes, and on cleavage face there appear slip lines as shown in Fig. 12, some of which are double or triple. At about 600 °C, fracture occurs along grain boundaries as shown in Fig. 11.

5. Consideration

5.1 On deformation

We see that the deformation which is made by formation and development of short slip lines in the specimen tested below the characteristic temperature differs from the deformation which is made by formation and development of long slip lines above that temperature. From this, we infer that the difference between these deformations is due to the difference between activation energies required to form these deformations. And above the characteristic temperature, we infer that appearance of easy deformation which is caused by increase of cyclic load is due to increase of stress energy, which is induced from the stress increase under increase of load.

However, below 500 °C, breakdown deformation generally increases with increase of testing temperature and the applied cyclic load decreases with increase of testing temperature. And below 500 °C, 9 % Al alloy can approximately be regarded as a solid solution of maximum Al amount, for the maximum Al amount solid solution is about 9.4 %, as shown in Fig. 13⁽⁹⁾; and the amount does hardly change by increase of testing temperature. Therefore we infer that this increase of breakdown deformation and this decrease of cyclic load with increase of testing temperature occur from such approximation, as 9 % Al maximum amount of solid solution, and from the unchangeability of the maxi-

mum amount. Further we see that obstruction⁽¹⁰⁾ of dislocation movement due to Al atoms is saturated; an increase, due to the obstruction, of tensile strength and hardness is very small; and easy deformation and lowering of the tensile strength occur from increases of movable dislocation^{(11) (12)} and vacancy concentration⁽¹²⁾ under the increase of testing temperature.

When the testing temperature is constant, breakdown deformation increases with increase of the cyclic load. Therefore we infer that this increase of breakdown deformation occur by increase of movable dislocation with increase of stress energy.

When the intercrystalline fracture, which is caused by the crack appearance and growth at grain boundaries, appears, breakdown deformation becomes lower. From Fig. 13, we see that β phase of Cu-Al alloy with 9.4 % Al appears from 565 °C. Therefore from this we infer that, at 600 °C, β phase, which is a phase change of α phase, already appears at grain boundaries abounding in dislocations. And we infer also that easiness of crack occurrence results from weakness⁽¹³⁾, due to the appearance of β phase, of grain boundaries and to appearance of brittleness⁽¹⁴⁾, and a decrease of breakdown deformation occurs owing to the brittleness⁽¹⁴⁾ resulting from the crack occurrence.

5.2 The number of load cycles and deformation

If instead of the number of the load cycles the testing time process is used, we see that curves in Figs. 5 and 6 are similar to creep curves

Fig. 12 Specimen tested on condition of cyclic load 6 kg, testing temperature 500 °C, the number 1.2×10^3 of load cycles to cause the fracture

Fig. 13 Thermal equilibrium diagram of Cu-Al alloy near 9 % Al

obtained under static load.

In the test, we could not measure deformation just before the fracture and could not keep the constant cyclic load just before that. Meanwhile at a start of this test, while we were adjusting the cyclic load to a certain requisite magnitude, a number of unknown loads worked on the specimen and caused considerable deformation.

Therefore we exclude the ranges before 20 % and after 80 % of the number $\bar{N}$ of load cycles to cause the fracture and discuss on the deformation in the range $0.2\bar{N} \sim 0.8\bar{N}$. If positions expressed by the numbers $0.2\bar{N}$ and $0.8\bar{N}$ and by the deformation at $0.2\bar{N}$ and $0.8\bar{N}$ are reference points, and if the distance between these positions (i.e. the differences between these numbers and between these deformations) reduces to unity, such

curves which express the relation between the number of load cycles and deformation are shown in Fig. 14 (a)~(d). From Fig. 14, we see that positions of these curves, which are obtained from data below 100 °C, become higher as the testing temperature rises, but those obtained above 100 °C become lower. And we see also that the positions of these curves become the higher with increase of the number of load cycles to cause the fracture, and these curves concentrate on the inclined straight line through points A and B shown in Fig. 14. Then we make such a coordinate, that the point A expresses $(0.2, c_1)$, B $(0.8, 1-c_2)$; $(0, 0)$ is at a distance -0.25 along the axis of abscissa and at a distance $-1.25c_1$ along the ordinate axis from A in the scale of Fig. 14, and $(1, 1)$ at 0.25 along that of abscissa and at $1.25c_2$ along

(a) Cyclic load 6 kg

(c) Cyclic load 16 kg

(b) Cyclic load 10 kg

(d) Cyclic load 26 kg

Fig. 14 [(The number of load cycles $- 0.2\bar{N}) / (0.8\bar{N} - 0.2\bar{N})] \bar{n}_0$ and [(deformation of $0.8\bar{N}$ - one of $0.2\bar{N}$)] $\bar{\epsilon}_0$, where $\bar{N}$ is the number of load cycles to cause the fracture

that of ordinate from B, where c_1 and c_2 are constant. A curve, which passes through points (0, 0), (0.2, c_1), (0.8, $1-c_2$) and (1, 1) and, in range (0.2, c_1)—(0.8, $1-c_2$), passes through the middle of dimension which the curves in Fig. 14 occupy, can be expressed by

$$\bar{\epsilon} = A^* \bar{n}^{1/3} \exp B^* \bar{n} \quad \left. \begin{array}{l} A^* = 0.13, \\ B^* = 2.0 \end{array} \right\} \dots\dots\dots (2)$$

where $\bar{\epsilon}$ means [deformation of the number N of load cycles/breakdown deformation] and $\bar{n}$ [N /the number of load cycles to cause the fracture]. And Eq. (2) is similar to the type of formula⁽¹⁵⁾ of Andrade's creep under static load⁽⁷⁾.

5.3 On minimum deformation rate ($d\epsilon/dN$)

Relation between the minimum deformation rate ($d\epsilon/dN$) and the number $\bar{N}$ of load cycles to cause the fracture, in Cu-Al alloy with 9% Al, is shown in Fig. 8. And the relation, demonstrated by data in literature^{(16)~(18)}, between minimum creep rate ($d\epsilon/dt$) (hr^{-1}) under static load and time process t^* (hr) to cause the fracture is shown in Fig. 15. From Fig. 15 the relation can be expressed by

$$\log_{10}(d\epsilon/dt) = -A^{**} \log_{10} t^* + B^{**} \quad \left. \begin{array}{l} A^{**} = 6/5, \\ B^{**} = -0.9 \end{array} \right\} \dots\dots\dots (1.2)$$

and Eq. (1.2) is almost similar to the formula described by Machlin⁽¹⁹⁾. And from Eqs. (1.1) and (1.2), we see that the relation between ($d\epsilon/dN$) and $\bar{N}$ is similar to that between ($d\epsilon/dt$) and t^* . Necessary factors, which make similarity of these relations, are the following conditions (I) and (II).

(I) Always, logarithm $\log_{10} \epsilon_0$ of breakdown deformation ϵ_0 is nearly a constant.

(II) $\log_{10}[(d\epsilon/dN)\bar{N}^m]$ is nearly a constant, where $m \cong 1$.

Fig. 15 Minimum creep rate ($d\epsilon/dt$) and time process t^* to cause the fracture in single phase alloys

(I) is verified from Figs. 5 and 6; and (II) is verified from (I) and Fig. 14, if $m=1$ for $m \cong 1$.

And if (I) and (II) are verified, $\log_{10}[(d\epsilon/dN)\bar{N}^m]$ becomes a constant and then Eq. (1.1) is verified. In the same way, if the conditions, corresponding to (II), of the creep under static load is verified, from Andrade's formula we see that $[\log_{10}(d\epsilon/dt)t^{*m}]$ becomes nearly a constant, where $m' \cong 1$.

5.4 Experimental formula of fatigue

Production process and size of specimens which are used on tensile test⁽⁸⁾ at high-temperature in vacuum are the same as ones in this test. And in the tensile test, we see that the relation between testing temperature T and breakdown load W , i.e. tensile load to cause the fracture, is shown in Fig. 16. And also when the number of load cycles to cause the fracture is constant, the relation between cyclic load and testing temperature is shown by opened circles in Fig. 16. From Fig. 16, we see that the slopes of these curves obtained by fatigue test are similar to that of the curve obtained by tensile test. Therefore at first we discuss an analysis of the breakdown load which is closely related to fatigue strength.

From Fig. 16, we infer that deformation is made of two mechanisms on long slip lines and on short slip lines, as shown in Fig. 17. However we put the function which expresses the break-

Fig. 16 Cyclic load w against testing temperature T . Opened circle denotes tested value, and full one denotes calculated one

down load W , as

$$\left. \begin{aligned} W &= W_0 \exp[-A'(T-T_0)^2] \\ W_0 &= 46.5 \text{ kg}, \quad A' = 14.8 \times 10^{-5} \text{ K}^{-2} \\ T_0 &= 360^\circ \text{K} \end{aligned} \right\} \dots\dots (3)$$

And the calculated values from Eq. (3) agree with the tested values as shown in Fig. 18.

From the wellknown relation⁽²⁰⁾, we define that deformation obtained at a certain temperature is expressed by

$$e_0' = a W_0^{*b} \dots\dots\dots (4)$$

where a and b are constant values and W_0^* is the applied load. Then from Eqs. (2) and (4), the deformation at the number N of load cycles is expressed by

$$\varepsilon = A_0 W^b N^{1/3} \exp B_0 N \dots\dots\dots (5)$$

The breakdown deformation, which verifies the condition (I), is expressed by

$$\log_{10} \varepsilon_0 = \log_{10} A_0 + b \log_{10} w + (1/3) \log_{10} \bar{N} + B_0 \bar{N} \log_{10} e = \text{constant} \dots\dots (6)$$

Fig. 17 Relation, between testing temperature T and load W to cause the fracture, in two mechanisms of deformation

Fig. 18 Tested value of breakdown load W and calculated value obtained from Eq. (3)

And by aids of Eq. (2) and condition $|B_0 \bar{N} \log_{10} e| \ll 1$, Eq. (6) is expressed by

$$b \log_{10} w = (1/3) \log_{10} \bar{N} - \log_{10} A_0 + \log_{10} \varepsilon_0 \dots\dots (7.1)$$

On the other hand, we see that the relation between cyclic load w and the number $\bar{N}$ of load cycles to cause the fracture is shown in Fig. 19, and this relation can be expressed by

$$\left. \begin{aligned} \bar{N} &= \bar{A} w^{\bar{B}} \\ \bar{B} &= 8 \end{aligned} \right\} \dots\dots\dots (7.2)$$

And Eq. (7.2) agree with Eq. (7.1). Therefore from the wellknown relation⁽²¹⁾ between $\bar{N}$ and w , we define again that the relation is Eq. (7.2).

Deformation rate in the tensile test done at high-temperature in vacuum is 0.03 mm/sec, and the time process to cause the fracture is about 3×10^2 sec. The number $\bar{N}_0$, which corresponds to that time process, of load cycles to the fracture is difficult to obtain from theoretical calculation, for $\bar{N}_0$ depends on deformation rate, load-deformation curve, etc. Then we assume that $\bar{N}_0$ is obtained empirically. And when $w = W$, $\bar{N}$ becomes $\bar{N}_0$ and from Eq. (7.2)

$$\bar{N}_0 = \bar{A} W^{\bar{B}} \dots\dots\dots (8.1)$$

$$\text{and } \bar{A} = \bar{N}_0 W^{-\bar{B}} \dots\dots\dots (8.2)$$

The from Eqs. (7.2) and (8.2) the fatigue formula is given by

$$\bar{N} = \bar{N}_0 (w/W)^{-\bar{B}} \dots\dots\dots (8.3)$$

$$\text{and } \bar{N} = \bar{N}_0 (w/W_0)^{-\bar{B}} \exp[-A'(T-T_0)^2] \dots\dots (8.4)$$

5.5 Agreement between fatigue formula and tested value

We make sure of agreement between Eq. (8.3) and tested value. Then the logarithmic expression of Eq. (8.3) is given by

$$\log_{10} \bar{N} = \log_{10} \bar{N}_0 - \bar{B} \log_{10} w + \bar{B} \log_{10} W \dots\dots\dots (8.5)$$

where $\bar{B} = 8$. And when $\bar{N}_0$ of Eq. (8.5) is 4×10^2 , the value calculated from Eq. (8.5) becomes one shown by full circle in Fig. 16, and agrees with the tested one shown by opened one.

6. Conclusions

Tensile fatigue test of Cu-Al alloy, with 9% Al, at high-temperature in vacuum was performed, and slip lines on fractured specimen was observed.

Fig. 19 Cyclic load w and the number $\bar{N}$ of load cycles to cause the fracture

Further, relationship between results of the present test and those of tensile test⁽⁷⁾ at high-temperature in vacuum is discussed. Thus as the result of the present investigation, the following conclusions are obtained:

(1) Below 500 °C, breakdown deformation increases with increase of cyclic load.

(2) Below the characteristic temperature at which considerable breakdown deformation begins and appears, breakdown deformation increases with the testing temperature, but the deformation and the increase of the deformation are small. And above the characteristic temperature, the deformation becomes considerably larger.

(3) The characteristic temperature tends to become lower as the cyclic load increases.

(4) Above 400 °C, cracks appear at grain boundaries. And at about 600 °C, the greater part of deformation is caused through mutual sliding and cracking of the boundaries.

(5) Below 500 °C, the fracture is a shear along cleavage planes. At about 600 °C, the fracture originates from the formation and growth of grain boundary cracks. And when the intercrystalline fracture appears, the breakdown deformation becomes small.

(6) [(The number of load cycles $-0.2\bar{N}$)/($0.8\bar{N}-0.2\bar{N}$)]-[(deformation-one of $0.2\bar{N}$)/(one of $0.8\bar{N}$ -one of $0.2\bar{N}$)] curves concentrate on a straight line, which passes through origin and has a tangent of 45 degrees, where $\bar{N}$ is the number of load cycles to cause the fracture. And the positions of those curves are higher as the cyclic load is larger.

(7) Relation between [the number of load cycles/ $\bar{N}$] ($\bar{n}$) and [deformation/breakdown deformation] ($\bar{\epsilon}$) can be expressed by

$$\bar{\epsilon} = A^* \bar{n}^{1/3} \exp B^* \bar{n}$$

$$A^* = 0.13, \quad B^* = 2.0$$

(8) Relation between the minimum deformation rate ($d\epsilon/dN$) and the number $\bar{N}$ can be expressed by

$$\log_{10}(d\epsilon/dN) = -A \log_{10} \bar{N} + B$$

$$A = 1.2, \quad B = 0.2$$

(9) Relation between breakdown load W and testing temperature T can be expressed by

$$W = W_0 \exp[-A'(T-T_0)^2],$$

$$W_0 = 46.5 \text{ kg}, \quad A' = 0.88 \times 10^{-5} \text{ K}^{-2},$$

$$T_0 = 360^\circ \text{K}$$

(10) Relation among testing temperature T , cyclic load w and the number $\bar{N}$ of load cycles to cause the fracture can be expressed by

$$\bar{N} = \bar{N}_0 (w/W)^{-\bar{B}} \exp[-A'(T-T_0)^2]$$

$$\bar{B} = 8, \quad \bar{N}_0 = 4 \times 10^2$$

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