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The interpretation of cyclic creep deformation mechanism of copper in terms of the anelastic recovery

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The cyclic creep deformation behaviour of copper has been studied in the temperature range of 0.4 to 0.5 T_m and under the constant stress range of $(\sigma/E) = 4 \times 10^{-4}$ to 10×10^{-4}. To see the effect of cyclic stress frequency, stress amplitude and the duration of the unloading time in a fixed frequency on cyclic creep behaviour, static and cyclic creep tests were conducted under the conditions mentioned above. The measured activation energies for static and cyclic creep were analysed in terms of the various experimental parameters. Anelastic behaviour during the unloading period was also studied to find out the possible assistance for the positive creep deformation in cyclic creep. Using the concept of anelastic recovery and the activation energy for the anelastic it is hypothesized that the accelerated cyclic creep deformation is controlled by the anelastic recovery during the unloading period.

1. Introduction

Because cyclic creep behaviour has a great significance in scientific and engineering view points, many studies have been carried out to interpret the deformation mechanism of cyclic creep [1–6]. Cyclic creep acceleration has been observed in lead [1], copper [2], aluminium [3, 4], aluminium alloys [7] and iron [8] while cyclic creep retardation has been reported in zinc [9], nickel alloys [10] and 316 stainless steel [11]. In addition, many theories have been proposed to explain the above results. These can be divided into two classes: (a) mechanisms assisted by point defects such as mechanically generated vacancies [1] or interstitials [6]; (b) line defect mechanisms such as dislocation oscillation [2] or cross-slip [3, 5]. But most experimental results allow only the phenomenological comparison to be made between cyclic and static cases in primary creep stage. Furthermore, all the previous cyclic creep results were obtained under constant peak load conditions, therefore, quantitative interpretation of the data was difficult.

This investigation was undertaken to determine the effects of the parameters such as stress amplitude, frequency, loading time and the peak stress values on the cyclic creep deformation mechanism. To do this, steady-state creep rates and activation energies for both static and cyclic creep under the same peak stress were obtained in the intermediate temperature range of 528 to 693 K (0.4 to 0.5 T_m). It was hoped to have a more mechanistic comparison of the deformation modes of cyclic and static creep. This comparison makes it possible to obtain the information on the role of the anelastic recovery process during cycling.

2. Experimental procedure

Electrolytic copper (>99.99%) was melted in a graphite crucible using an induction furnace to give the chemical composition of 99.94% Cu, 0.03% Fe and 0.03% Pb. The slabs were homogenized for 12 h at 1173 K and cold rolled

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into sheets of 1 mm thickness. Plate type creep test specimens with a gauge length of 25 mm and a width of 4 mm were machined and annealed for 2 h at 1023 K in a vacuum sealed Vycor tube to give an average grain size of 0.04 mm.

Both the static and cyclic creep tests were performed under a constant peak stress range of 42 to 111 MPa ($\sigma/E = 4$ to 10×10^{-4}) and at the test temperature range of 543 to 679 K (0.4 to 0.5 T_m). For static tests, to maintain constant creep stress, a creep machine equipped with an Andrade–Chalmers constant stress arm was used. For cyclic tests a specially designed load elevating device [12] was attached to the Andrade–Chalmers arm. Using this device, peak stress, stress amplitude, frequency and loading–unloading time could be kept constant throughout a cyclic creep test.

Test temperature was kept constant within ± 1 K using an infrared reflection furnace. Strain was measured by a Schaevitz model HR1000 LVDT with an accuracy of 4×10^{-5} sec^{-1}.

It has been shown that the cyclic creep behaviour is affected by test temperature, peak stress, stress amplitude, frequency, loading–unloading time and stress wave form [3, 5, 7, 11, 13]. Among these parameters, the effects of stress amplitude, frequency and unloading time on the cyclic creep deformation behaviour have been studied. To maintain constant (σ/E) for the creep tests, stress has been normalized with the Young's modulus at that test temperature. The data for the Young's modulus of copper was obtained from Orlov's [14] experimental results.

3. Experimental results

3.1. The effects of stress frequency and unloading time

To investigate the effect of stress frequency (f is cycles per min, cpm) on the cyclic creep rate and the activation energy of cyclic creep deformation, tests have been conducted with five different frequencies, that is 0.1, 0.3, 0.5, 1.0 and 3.0 cpm. For convenience, the ratio of cyclic to static creep rate for the corresponding test conditions of temperature and stress are plotted against the period, that is the time spent for one cycle (Fig. 1). Before starting to discuss our results, it may be worthwhile to define the meaning of cyclic acceleration. For this investigation most of the cyclic creep tests are conducted with a trapezoidal stress wave shape. Since loading and unloading is accomplished within 1 sec almost half of the time for one period is for load at peak stress and the other half is for the unloaded state. Therefore, if we count the time at load (half a period) only for the calculation of cyclic creep rate, it will be twice that of the rate calculated with the time for the whole period. The cyclic creep rate used in this work is obtained by using the latter and if the ratio of cyclic to static creep rate is larger than 0.5, we determine that cyclic creep acceleration has occurred.

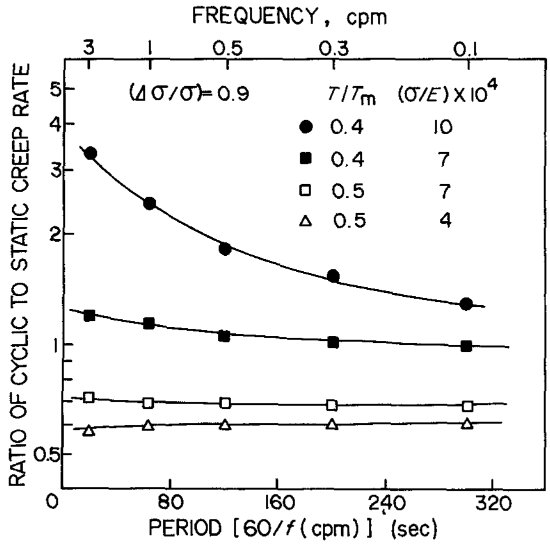

Figure 1 The ratio of cyclic to static creep rate ($\dot{\epsilon}_c/\dot{\epsilon}_s$) against the inverse of stress frequency (period).

From the plot in Fig. 1, it can be seen that cyclic creep acceleration becomes more significant with lower temperature and higher stress. At 0.5 T_m, a very small amount of acceleration is observed and it is not influenced by the stress frequency. However, at 0.4 T_m, the acceleration becomes very significant and it is affected by the frequency: as the frequency increases the acceleration becomes greater.

In Fig. 2, the activation energies for the static and cyclic creep deformation in the vicinity of 0.4 T_m are shown for two different peak stresses and four different frequencies (for cyclic creep). Those values at the temperature range of 0.5 T_m are not plotted in this fashion, however, they are summarized in Fig. 3 against the period. At 0.5 T_m, the energy is observed to be slightly increased with the period. On the other hand at 0.4 T_m, for short periods (high frequency) the activation energy value is found to be very small but increases significantly as the period increases. However, the

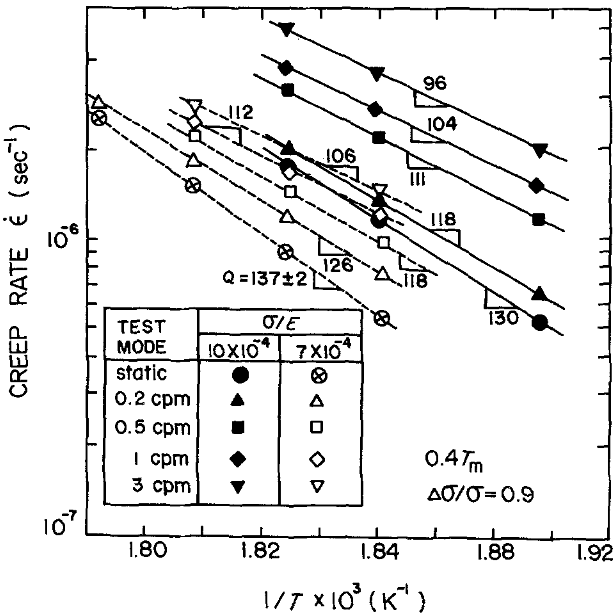

Figure 2 Steady state creep rates for static and cyclic creep at various frequencies in the vicinity of $0.4\,T_m$ plotted against the inverse of temperature.

energy for the cyclic creep is always smaller than that for the static creep.

To see the effect of the possible recovery process occurring during off-load on the behaviour of the cyclic creep deformation during on-load, the off-load time has been varied within the fixed period of time for the constant frequency of 3 cpm. In Fig. 4, the creep rate ratio, $\dot{\epsilon}_c/\dot{\epsilon}_s$, is plotted against the unloading time period for a fixed stress frequency and amplitude at 0.4 and $0.5\,T_m$. As the peak stress increases and the temperature decreases, the creep rate ratio increases very significantly, (cyclic creep acceleration), under the condition of same on-load and off-load time. However, towards $0.5\,T_m$, in which cyclic creep retardation is observed, the ratio is continuously decreasing with the off-load time, and no effect of peak stress is observed. In Fig. 5, for the same stress frequency and amplitude as in Fig. 4, the cyclic creep activation energy against off-load time is seen to show the minimum value of the activation energy for the same on-load and off-load time period. As it is observed in Fig. 4, the influence of the off-load period is more significant at the lower temperature.

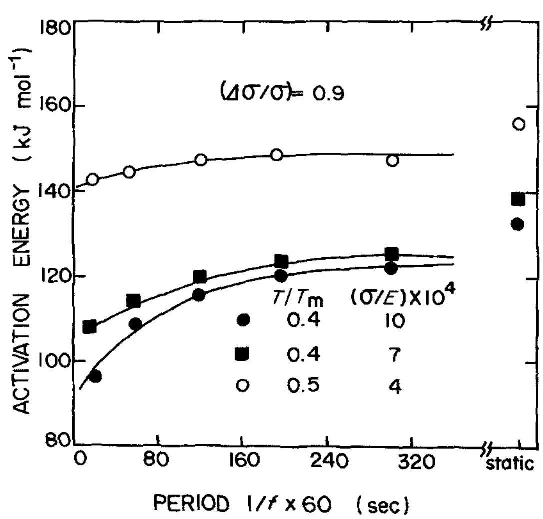

Figure 3 Activation energy of creep deformation against the inverse of frequency of the cyclic creep.

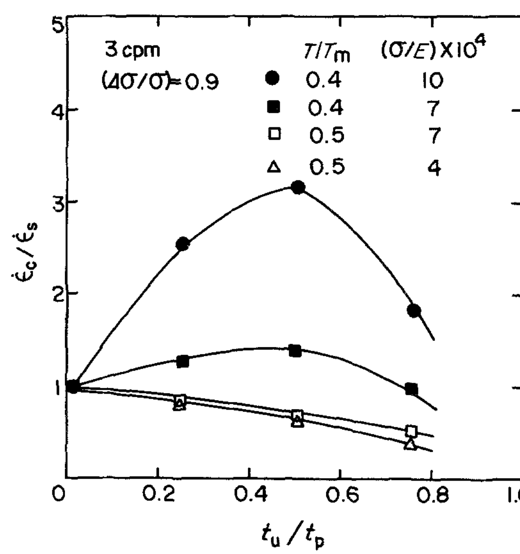

Figure 4 The ratio of cyclic to static creep rate against the ratio of off-load to total time in a period.

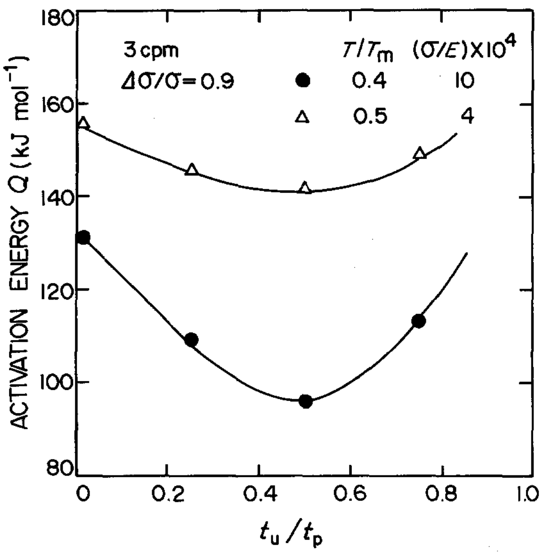

Figure 5 The activation energy of cyclic creep against the ratio of off-load to a period at the constant frequency of 3 cpm.

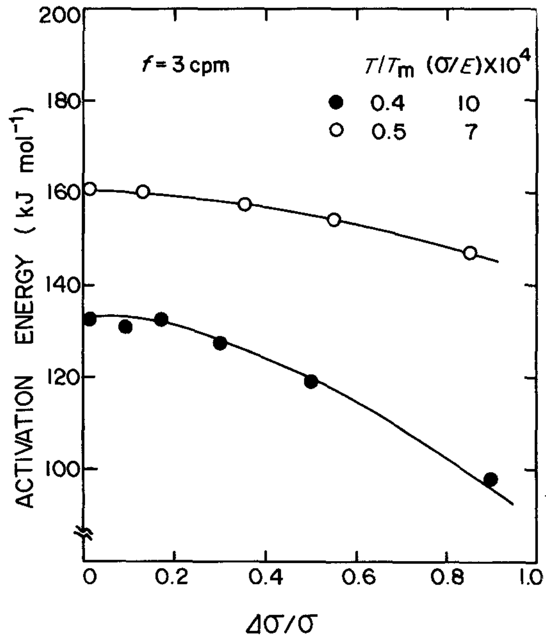

Figure 7 The variation of the activation energy with the stress amplitude.

3.2. The effects of stress amplitude

Under the constant peak stress (111 MPa = 1.0×10^{-3} E) and fixed frequency (3 cpm), the effects of cyclic stress amplitude on the creep rate and on the activation energy were studied.

At $0.4\,T_m$, as shown in Figs. 6 and 7, cyclic creep acceleration is observed and the degree of acceleration is sharply increased with the stress amplitude, however, as far as the activation energy is concerned, it is observed that the energy does not vary with the increasing amplitude up to about 15% of the peak stress. But as the amplitude increases above 15%, the activation energy decreases very sharply. On the other hand, at $0.5\,T_m$ where cyclic retardation is observed, even though the amplitude is increased very significantly the activation energy is decreased only slightly.

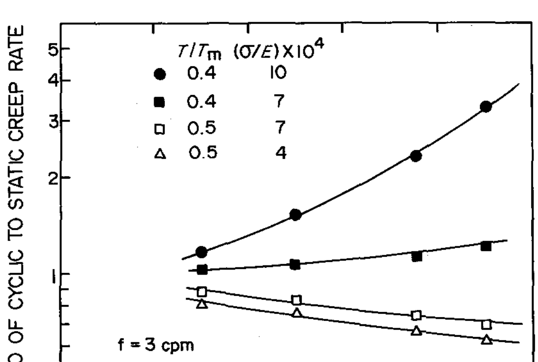

Figure 6 The ratio of cyclic to static creep rate against the ratio of amplitude to peak stress.

4. Discussion

On loading to the peak stress at the end of the off-load period, the rate of creep deformation is observed to be very much higher than that at the end of the previous on-load period. As the loading time continues the deformation rate decreases to show typical primary creep phenomenon. The presence of this small primary region is evidence of the fact that the structure has recovered to a "softer" state during off-load time, that is, the behaviour of anelastic recovery with reduced stress is related mainly to the "softening" of the structure. (The effect of grain boundary sliding on the anelastic strain will be discussed later.)

Some investigators [15, 16], suggested that anelastic strain was caused by unloading due to rearrangement of three-dimensional networks of dislocations, but they could not completely account for the relatively large anelastic strain compared to elastic strain. Assuming that the residual stress during unloading was related to anelastic behaviour in nickel and nickel–chromium alloys, Gibbons *et al.* [17] have derived an equation for the anelastic strain rate as:

$$\dot{\epsilon} = A \cdot \exp\left(-\frac{Q}{RT}\right) \sinh \frac{V \cdot \Delta\sigma}{RT} \left[1 - \frac{\epsilon_a(t)}{\epsilon_a^0}\right] \quad (1)$$

where: A is the frequency factor; Q is the activation energy; V is the activation volume; ϵ_a^0 is the total elastic strain after an infinitely long time; and $\epsilon_a(t)$ is the elastic strain after time t.

As shown in Fig. 4, at 0.4 T_m, cyclic creep rate increases with off-load time at constant frequency (f = 3 cpm). This result suggests that the anelastic recovery is occurring more effectively in the off-load period than the dynamic recovery in the on-load period. Therefore, it is hypothesized that the rate controlling mechanism of cyclic creep deformation is predominated by the anelastic recovery process. Taking the natural logarithm of Equation 1 and differentiating it with respect to the inverse of the absolute temperature, one obtained the following relationship:

$$Q_a = Q - V \cdot \Delta\sigma \left[1 - \frac{\epsilon_a(t)}{\epsilon_a^0}\right] \quad (2)$$

where: Q_a is the activation energy of anelastic recovery, which is assumed to be equal to that of cyclic creep, Q_c; and Q is the activation energy of anelastic recovery with $\Delta\sigma = 0$, that is the activation energy for static creep.

To see more clearly the rate of anelastic deformation phenomenon in the steady state both of cyclic and static creep the following tests have been conducted. For cyclic creep, the cyclic mode had been stopped at the off-load period so that the specimen could be anelastically recovered under 10% of the peak stress for long time and for static creep 90% of the peak stress had been reduced to be recovered anelastically. The anelastic strain was measured with unloading time at three different temperatures in the vicinity of 0.4 T_m. The activation energy for the anelastic deformation has been estimated from the plot of the anelastic strain rate at certain levels of residual stress, $\Delta\sigma\{1 - [\epsilon_a(t)/\epsilon_a^0]\}$, against the inverse of the temperature.

As shown in Fig. 8, the activation energy for the anelastic recovery is increasing with decreasing residual stress (or increase in time for the anelastic recovery) and is similar for static and cyclic creep at the same amount of the residual stress. (In Fig. 8 $\Delta\sigma$ has been modified by subtraction of σ_0, the friction stress, and the meaning of the modification will be explained later.)

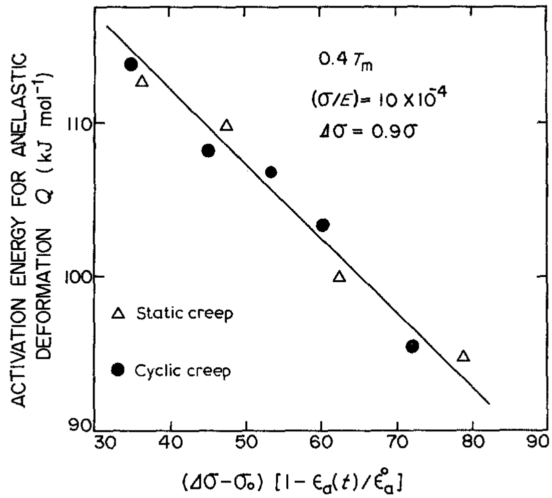

Figure 8 The variation of the activation energy of anelastic deformation with the residual stress.

To see the variation of the anelastic strain with unloading time, the value of $\log\{1 - [\epsilon_a(t)/\epsilon_a^0]\}$ has been plotted against the unloading time in Fig. 9. It is clearly shown in the figure that $\log\{1 - [\epsilon_a(t)/\epsilon_a^0]\}$ is linearly decreasing with unloading time for the specimens both in static and cyclic creep. To see if it is a general phenomenon, the experimental data from Gibeling and Nix [18] for copper and aluminium have been plotted on the same figure. As one can see, their data also satisfy the linearity and all the plots are satisfied by the equation below:

$$1 - \left(\frac{\epsilon_a(t)}{\epsilon_a^0}\right) = 0.9 \exp(-kt) \quad (3)$$

where k is the constant which depends on the

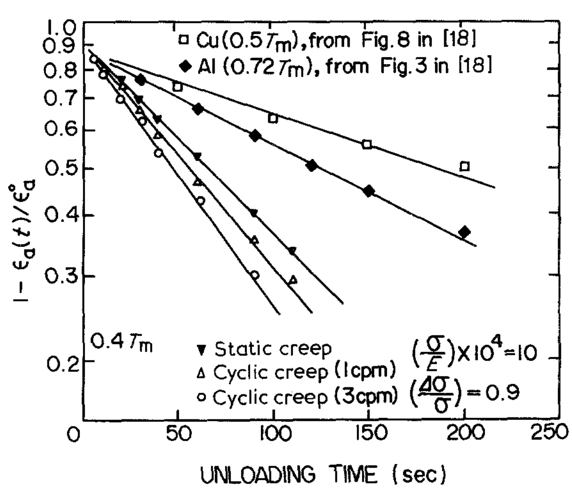

Figure 9 The ratio of residual to total anelastic strain against off-load time at 0.4 T_m.

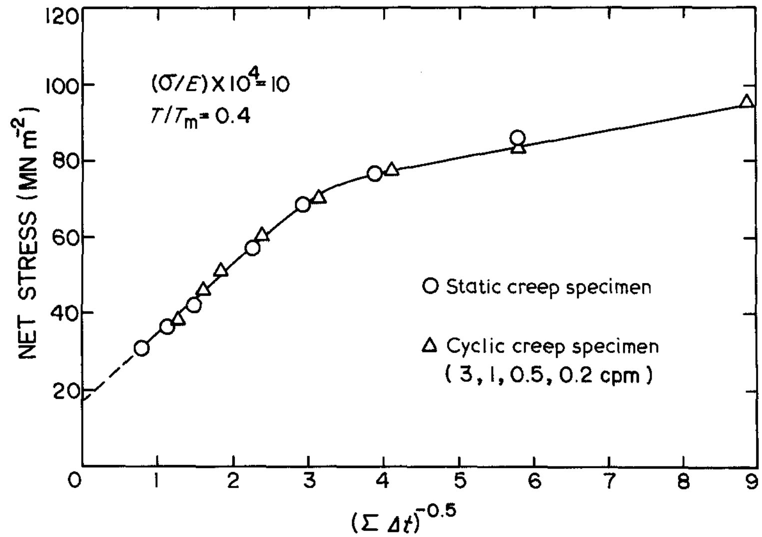

Figure 10 The value of the friction stresses of static and cyclic creep specimens.

material and test conditions. The factor of 0.9 is related to the "fast anelastic contraction" immediately after unloading. The amount of fast anelastic contraction was about 10% of the total anelastic contraction, ϵ_a^0, which may be related to unbowing of the bowed dislocations. This situation was also observed by Lupinc and Gabrielli [19], and they have studied the effect of grain size on the anelastic recovery. They observed that the grain size strongly affected the total relaxed strain; however, at the early stages of relaxation, with fast anelastic strain rate, the effect of the grain size was not so significant as at the later stages of slow strain rate where the influence was strong.

In this work, since the typical off-load period is only 10 sec, the effect of grain boundary sliding on the anelastic recovery may not be so significant in such a short initial period of time.

It was experimentally observed that there has to be a critical amount of stress drop for anelastic recovery to occur in the specimen. This critical stress was experimentally observed to be the same as the "friction stress" measured by the stress dip extrapolation technique proposed by Davies *et al.* [20]. Some of the results for the friction stress, σ_0, measured for the conditions of $0.4\,T_m$ and $(\sigma/E) = 10\times10^{-4}$ are shown in Fig. 10. The friction stress was found to be the same for the static and cyclic creep specimens and was not affected by the cyclic frequencies. The values of the friction stresses were 17 and 15 MPa for the peak stress of $(\sigma/E) = 10\times10^{-4}$ and $(\sigma/E) = 7\times10^{-4}$, respectively.

Considering this, it may be reasonable to subtract σ_0 from the value of $\Delta\sigma$ in Equation 2. Therefore, using Equation 3 and modifying $\Delta\sigma$ one can rewrite Equation 3 as follow;

$$\Delta Q = Q_s - Q_c = 0.9\,V(\Delta\sigma - \sigma_0)\exp(-kt) \quad (4)$$

where ΔQ is the difference between the activation energies of static and cyclic creep deformation. To prove the validity of our hypothesis, the value of $0.9\,V(\Delta\sigma - \sigma_0)\exp(-kt)$ has to be calculated and compared with the value of $Q_s - Q_c$ which is independently obtained from the experimental measurement of the activation energies.

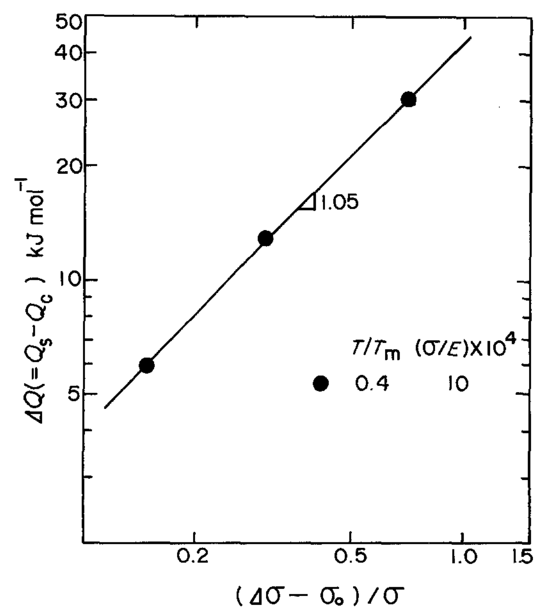

Figure 11 The activation energy difference between static and cyclic creep against friction stress compensated stress amplitude.

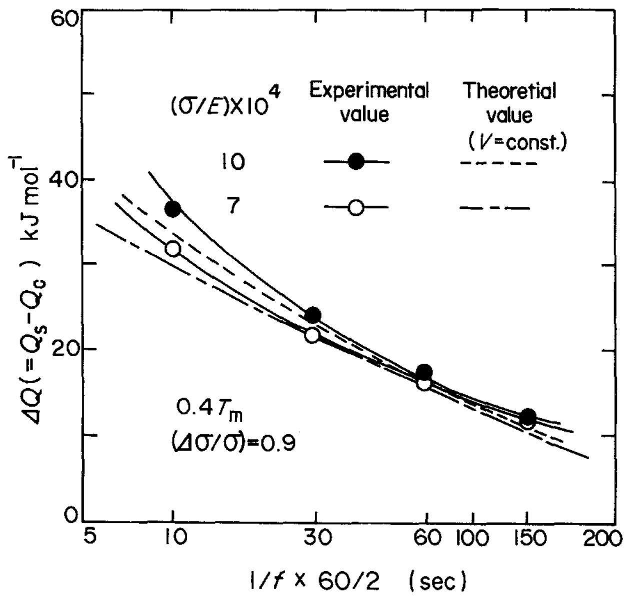

Figure 12 The activation energy difference between static and cyclic creep against the inverse of frequency.

The activation volume (V) was obtained from the slope of the plot shown in Fig. 8 and the value was obtained to be about $70\,b^3$ which indicates motion of the jogs is the possible rate controlling process [21]. From Equation 4 one may realize that if the value of V is constant for the constant value of k and t, then ΔQ has to be linearly proportional to the value of $(\Delta\sigma - \sigma_0)$, and this relation is shown in Fig. 11.

To calculate the value of $0.9\,V\,(\Delta\sigma - \sigma_0)\,\exp(-kt) = \Delta Q$, the proper values are substituted into Equation 4 and the results are plotted in Fig. 12 along with the experimentally measured values of ΔQ. (For the value of k see Table I.) Within experimental error, the calculated values of ΔQ are found to closely match the experimentally measured ones. This result implies that the cyclic creep process is controlled by the anelastic recovery process during unloading period as previously hypothesized.

5. Conclusions

1. At $0.4\,T_m$, as the stress frequency, peak stress and stress amplitude are increasing, the cyclic creep rate of pure copper is increasingly accelerated compared to the equivalent static creep rate. However, at $0.5\,T_m$, slight cyclic creep acceleration is observed and there is no significant effect of the frequency, stress and amplitude on the cyclic creep rate.

2. Cyclic creep rate increased with unloading time at constant stress frequency. This implies that anelastic recovery during unloading time operates more effectively than dynamic recovery during the loaded period does for the "softening" of the structure.

3. The activation energy for cyclic creep deformation is found to be similar to that for anelastic deformation, during the unloading stage.

4. Based on the anelastic behaviour of the crept specimens and the measured activation energies, it is suggested that the deformation mechanism of cyclic creep is controlled by the anelastic recovery of the dislocation structure during the unloading period.

TABLE I Values of relaxation constant obtained from unloading tests in steady state

Frequency (cpm)	Unloading time (sec)	Relaxation constant k (sec^{-1})	
		$(\sigma/E) = 10 \times 10^{-4}$	$(\sigma/E) = 7 \times 10^{-4}$
3	10	1.39×10^{-2}	1.31×10^{-2}
1	30	1.28×10^{-2}	1.16×10^{-2}
0.5	60	1.13×10^{-2}	9.80×10^{-3}
0.2	150	1.05×10^{-2}	8.86×10^{-3}

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