THERMALLY ACTIVATED PLASTIC FLOW UNDER TENSION- TENSION CYCLIC LOADING CONDITIONS

J. S. Mshana
Department of Mechanical Engineering, University of Dar es Salaam
P.O. Box 35131 Dar es salaa, Tanzania

ABSTRACT

The transition state theory of rate processes was utilized to describe cyclic plastic deformation behavior of a near eutectoid, Zn-Al alloy. The results of the present and previous studies showed that within the high stress and low temperature range where thermally activated plastic flow in cyclic (load and strain controlled) deformation can be approximated with activation over a single energy barrier, strain controlled cyclic deformation is essentially a stress relaxation process while load controlled cyclic deformation is a creep process. The material structural characteristics determined from stress relaxation, creep, load and strain controlled cyclic loading experimental results were identical, leading to the conclusion that load and strain controlled cyclic deformations are different manifestations of the same basic process, depending on the control condition. Consequently, it was recommended that stress relaxation and creep can be employed to determine the material structural characteristics which can then be used to predict the cyclic deformation behavior, using the constitutive laws developed in the present and previous studies.

INTRODUCTION

A sound constitutive equation must be based on rigorously derived, physical theory and conform to experimental observations. It was shown by Krausz and Eyring [1] and others [2] that thermally activated plastic flow and chemical reactions are essentially identical processes, since both are solely the consequence of breaking and establishing of atomic bonds. Because of this fundamental and general fact, plastic deformation was considered as a chemical reaction in which the composition remains unchanged but the atomic configuration changes. Subsequently, chemical kinetics, based on statistical mechanics (or statistical thermodynamics) was widely utilized [1-9] to describe thermally activated plastic flow of many materials under monotonic loading conditions.

In previous studies by the author [10-12] it was demonstrated that the rate theory (rigorously derived, physical theory), based on statistical mechanics can also be used to describe plastic flow under repeated, cyclic loading conditions. While the cyclic deformation behaviour cannot, in general, be predicted from the analysis of stress relaxation and creep experimental results, the studies showed that under certain physically reasonable conditions, the constitutive parameters determined from stress relaxation can be used to predict the cyclic deformation behavior. It was shown further that within a high stress and low temperature range [low temperature range is defined as T $\leq$ 0.4Tm where Tm is the melting temperature (absolute)] where the rate of thermally activated plastic flow can be approximated with activation over a system of two sequential energy barriers, strain controlled cyclic deformation is essentially a stress relaxation process. The present paper extends this work to establish a similar relationship between load controlled cyclic deformation behaviour and creep. It will be shown that under the special conditions, load and strain controlled cyclic deformations are different manifestations of the same basic process, depending on the control condition.

Thermally Activated Plastic Flow

Plastic deformation is generally produced by the motion of dislocations under the drive of the applied shear stress [1-9]. In most cases, it is rate dependent (and, therefore, temperature dependent); that is, thermally activated. It was shown by Krausz and Eyring [1] that thermally activated plastic flow and chemical reactions are essentially identical processes, since both are solely the consequence of breaking and establishing of atomic bonds. The rigorous physical foundation of absolute rate theory was established by Eyring in 1936 [13] and it was incorporated into dislocation theory by Orowan [14]. Consequently, the constitutive equation for thermally activated plastic flow was expressed as [1-9, 14]

$$\dot{\varepsilon}_p = (\frac{1}{M}) b \rho_m \bar{v} = (\frac{1}{M}) b \rho_m \bar{l} \kappa \qquad (1a)$$

and in simple kinetics as

$$\dot{\varepsilon}_p = \frac{1}{M} b\rho_m \bar{l}(\kappa_f - \kappa_b) \tag{1b}$$

where $\dot{\varepsilon}_p$ is the plastic tensile strain rate, M is the Taylor orientation factor relating the tensile stress σ and tensile strain ε to the shear stress $\tau(= \sigma / M)$ and shear strain $\gamma(= M\varepsilon)$ resolved in the rate-controlling slip system, b is the Burger's vector, ρ_m is the mobile dislocation density, $\bar{l}$ is the distance travelled by the dislocation between obstacles, $\bar{v}$ is the average dislocation velocity, and κ is the overall rate constant which represents the simplest possible combination of the fundamental rate constants κ_f and κ_b which were derived from statistical mechanics as [1]

$$\kappa_f = \frac{kT}{h} \exp - \frac{\Delta G_f}{kT} \tag{2a}$$

and

$$\kappa_b = \frac{kT}{h} \exp - \frac{\Delta G_b}{kT} \tag{2b}$$

In Eqs. (2), k is the Boltzmann constant, T is the absolute temperature, h is the Planck's constant, ΔG is the apparent free energy and the subscripts f and b refer to the forward and backward activations, respectively over a single energy barrier. The apparent free energy is the energy needed from the thermal fluctuations of the atoms to cause dislocation motion, and it is expressed as [1]

$$\Delta G_f = \Delta G_f^+ - W_f(\tau) \tag{3a}$$

and

$$\Delta G_b = \Delta G_b^+ + W_b(\tau) \tag{3b}$$

where ΔG+ is the free energy of activation and is equal to the chemical, bond energy associated with the atoms that take part in the dislocation movement; W(τ) is the work contributed by the shear stress τ which causes the plastic flow. Thermally activated plastic deformation is often controlled by a system of energy barriers which may form either a consecutive system, a parallel system, or a combination of these two types. Hence, to obtain a physically meaningful description of the experimental results, a kinetics analysis [1,3,4] has to be carried out first, that will give the appropriate system of energy barriers. Then, as it is practiced in chemical kinetics studies, the combination of the individual rate constants or the overall rate constant κ can be determined. The required activation parameters are determined from the evaluation of the experimental results and from the testing conditions. It was established by Krausz and Eyring [1] and others [2-9] that Eqs. (1) lead to very good description of the behavior of many materials under a variety of different monotonic deformation processes. In the following, the application of this theory to describe load controlled cyclic deformation behavior and creep will be presented.

Load Controlled Cyclic Loading

Constant Internal Stress

During cyclic deformation, the total strain rate $\dot{\varepsilon}$ is the sum of two components: the elastic strain, rate $\dot{\varepsilon}_e$ and the plastic strain rate $\dot{\varepsilon}_p$. That is

$$\dot{\varepsilon} = \dot{\varepsilon}_e + \dot{\varepsilon}_p \tag{4}$$

The elastic strain rate is related to the shear stress rate as

$$\dot{\varepsilon}_e = \frac{\dot{\sigma}_a}{E} = \frac{M\dot{\tau}_a}{E} \tag{5}$$

where E is the combined elastic modulus describing the net elastic response of the test specimen and grip assembly.

In the simplest deformation kinetics where thermally activated plastic flow in load controlled cyclic deformation can be approximated with activation over a single energy barrier, the plastic strain rate is

$$\dot{\varepsilon}_p = \left(\frac{1}{M}\right) b\rho_m \frac{kT}{h} \bar{l} \exp - \frac{\Delta G_f^+ - W_f(\tau_{eff})}{kT} \tag{6}$$

The mechanical energy W(τ_{eff}) is usually a linear function of the applied shear stress and is expressed by a relation of the form [1]

$$W_f(\tau_{eff}) = V_f(\tau_a - \tau_i) \tag{7}$$

since $\tau_{eff} = \tau_a - \tau_i$, where τ_a is the applied shear stress, τ_i is the internal shear stress representing the resistance of the material to dislocation motion, and V_f is the activation volume or the product of the area swept out by the dislocation during a thermally activated movement and the Burger's vector, b, of the dislocation. The mobile dislocation density, ρ_m, is essentially an experimentally measurable quantity and is expressed in terms of stress or strain. A widely used form was introduced by Johnston [15], that is

$$\rho_m = \rho_m^o + B\varepsilon_p \tag{8}$$

where ρ_m^o is the mobile dislocation density measured at the beginning of plastic flow and is thus an empirical parameter that represents the previous deformation (state of the structure) history. It is outside of the theory of deformation kinetics and of the theory used here: it is also a microstructural feature to be measured by the method given in this report. The factor B is also measured by direct dislocation density observation and expresses the multiplication of dislocations in function of the strain. Eqs. (6), (7), and (8) can be combined and rearranged as

$$\frac{d\varepsilon_p}{\rho_m^o + B\varepsilon_p} = \left(\frac{A_f}{\rho_m}\right)\exp\frac{V_f(\tau_a - \tau_i)}{kT}dt \tag{9}$$

where

$$A_f = \frac{1}{M} b\rho_m \frac{kT}{h} \bar{l} \exp - \frac{\Delta G_f^+}{kT} \tag{10}$$

For the purpose of the present discussion, it is considered that cyclic plastic deformation takes place at constant internal stress, that is, the variations in the internal stress are negligibly small. During load controlled cyclic deformation, the applied stress is a periodic, random, or complex function of time. If y(t) is defined as

$$y = \int_0^t \exp\frac{V_f(\tau_a - \tau_i^o)}{kT}dt \tag{11}$$

then the integration of Eq. (9) leads to

$$\varepsilon_p = \frac{\rho_m^o}{B}[\exp A_f^1 By - 1) \qquad (12)$$

where

$$\rho_m A_f^1 = A_f$$

That is, within the stress and temperature range where the rate of plastic flow during cyclic deformation can be approximated with activation over a single energy barrier and occurs by dislocation movement and multiplication, the plastic strain increases exponentially with time. However, as straining proceeds, some of the mobile dislocations may loose their mobility through interactions with other dislocations (annihilation), pinning by solute atoms, or will be lost by emission through the surface. Microstructural studies [16] have shown that during cyclic loading, the mobile dislocation density of some materials increases rapidly at the beginning of load cycling and reaches saturation after a few cycles. Hence, for materials with negligible (net) dislocation multiplication, i.e., $B \rightarrow 0$, Eq. (12) becomes

$$\varepsilon_p \approx A_f y \qquad (13)$$

Consequently, the total strain during load controlled cyclic deformation is expressed as

$$\varepsilon = \varepsilon_0 + \frac{M(\tau_a - \tau_0)}{E} + A_f y \qquad (14)$$

For creep, $\tau_a = \tau_0$ = constant and the total strain is expressed in function of time as

$$\varepsilon = \varepsilon_0 + [A_f \exp \frac{V_f(\tau_0 - \tau_i^o)}{kT}]t \qquad (15)$$

while the strain rate is

$$\varepsilon = A_f \exp \frac{V_f(\tau_0 - \tau_i^o)}{kT} \qquad (16)$$

The conclusion that follows from eqs. (14), (15) and (16) is an important one: creep deformation process is a special case of stress controlled cyclic deformation. Consequently, it is anticipated that creep tests can be used to measure the constitutive parameters A_f and V_f that represent the microstructure which can then be used in the development of the constitutive equation of the more complicated cyclic deformation behavior. Hence, over the temperature, stress, and time range where thermally activated plastic flow in stress controlled cyclic deformation and creep can be approximated with activation over a single energy barrier, Eqs. (15) and (16) can be used to evaluate the constitutive parameters for the cyclic stress deformation process where the variations in the internal stress are negligible.

Linear Work Hardening

Consider that during load controlled cyclic loading, the internal stress increases linearly with the plastic strain as

$$\tau_i \approx \tau_i^o + \frac{H}{M}\varepsilon_p \qquad (17)$$

where τ^o is the internal stress at the beginning of the experiment and H is the work hardening coefficient. Within the high stress and low temperature range where the rate of plastic flow during work hardening can be approximated with activation over a single energy barrier, the constitutive equation becomes

$$\dot{\varepsilon}_p = A_h \exp[\frac{V_h}{kT}(\tau_a - \tau_i^o - \frac{H}{M}\varepsilon_p)]$$

or

$$\int_0^{\varepsilon_p} \exp\frac{V_h H \varepsilon_p}{kTM} d\varepsilon_p = A_h \int_0^t \exp\frac{V_h(\tau_a - \tau_i^o)}{kT} dt \qquad (18)$$

where the subscript h signifies that the activation parameters are associated with the work hardening mechanism, such as dislocation pile-up against obstacles, intersection mechanisms, etc. It is considered that the variation of the mobile dislocation density with time is negligible. Krausz and Craig [17], Wyatt [18], and others [1,19,20] have shown that the activation volume, V_h, evaluated from constant stress creep and from stress relaxation experimental results is inversely proportional to the initial stress, τ_0. In the special case of uniform obstacles, Essmann [21] showed that $V_h . \alpha . l . \alpha . 1 / \tau_o$, where l is the mean free length of mobile dislocation segments. Hence, during (constant amplitude) cyclic loading, the activation volume V_h is inversely proportional to τ_{max} since the changes in the mean free length of the mobile dislocation segments may be considered as irreversible. The plastic strain due to work hardening under cyclic loading conditions is then obtained from the integration of Eq. (18) as

$$\varepsilon_p = \frac{kTM}{V_h H}\ln[\frac{V_h H A_h}{kTM}\int_0^t \exp\frac{V_h(\tau_a - \tau_i^o)}{kT}dt + 1] \qquad (19)$$

For constant stress creep, $\tau_a = \tau_0$ = constant. Eq. (19) then becomes

$$\varepsilon_p = \frac{kTM}{V_h H}\ln[\frac{V_h H A_h}{kTM}\exp\frac{V_h(\tau_0 - \tau_i^o)}{kT}t + 1] \qquad (20)$$

Eq. (20) describes low temperature creep as a function of time. When the first term in the argument is much greater than unity, the plastic strain versus the natural logarithm of time relation is represented by a straight line. The slope of the curve is inversely proportional to the activation volume and from this V_h can be evaluated. This has been found to be the behavior in numerous experiments [1,17-21].

Fig. 1 shows the effect of cyclic stress on the plastic strain. The curves were calculated by using Eqs. (19) and (20) for cyclic loading and creep, respectively. A simple triangular load waveform was assumed while the procedure to evaluate the integral in Eq. (19) is presented elsewhere [11,12]. The figure shows that the plastic strain (after time t) is smaller under the cyclic stress than that under constant stress (equal to the maximum stress during cyclic loading) creep. The analysis also reveals that for a given maximum stress, the greater the stress amplitude the smaller is the plastic strain. That is, the higher the applied shear stress range, the greater is the cyclic hardening and hence the smaller is the accumulated plastic strain. The cyclic stress thus hardens the material. This behavior is sometimes referred to as "cyclic stress retardation".

The phenomenon of cyclic stress retardation has been observed experimentally by several investigators [22-25]. Shety and Meshii [22] observed the cyclic stress hardening behavior in Aluminum single crystals that were tested at 77K. The behavior was also observed in zinc [23] at 303K, and in many other materials [24,25]. The experimental observations confirm the results of the present analysis that the plastic strain measured during cyclic stress hardening is smaller than that measured during constant stress (equal to peak load) creep.

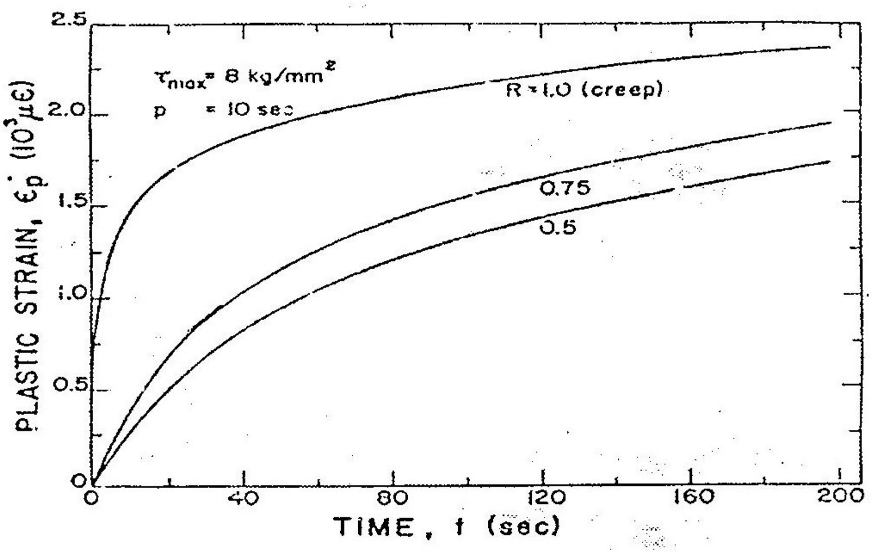

Fig. 1 **The effect of cyclic stress hardening on plastic strain** (the curves were calculated using Eq.. (20) for creep (R = 1) and Eq. (19) for cyclic loading. The stress ratio R = τ_{min} / τ_{max}. The parameters are:$V_h = 1100b^3$, = 3.55 eV, H/M = 157 kg/mm2, = 1.8 kg/mm2, T = 300 K, $\delta\rho_t$ kT/h = 12 sec^{-1}, and $\varepsilon_{p,o} = 0$. p is the cycle period).

In general, however, the creep rate in metals may either increase and/or decrease upon cyclic loading depending on the combination of the experimental variables (temperature, stress amplitude, frequency, etc.). That is, load cycling can cause either softening of the metal which leads to increase in the strain rate or hardening which is associated with decrease in strain rate. Often, however, the hardening and softening processes are not separate: they may operate simultaneously [22] during cyclic deformation. The application of the transition state theory to describe the simultaneous cyclic softening and hardening behavior is presented elsewhere [26].

Experimental Details

Material

The material under investigation was a commercial grade (marketed as Noranda Z-500), near eutectoid Zn-Al superplastic alloy of nominal composition: Al 25 Wt %, Cu 5 Wt %, Mg 0.05 Wt %, Zn balance. The material was selected because, as determined in a previous investigation [8] on constitutive laws, this alloy exhibits stress relaxation to the extent of complete unloading (it has very low internal stress), even at room temperature. Its extreme deformation behavior lends itself to illustrate the application of deformation kinetics to describe cyclic plastic deformation and to the investigation of rate controlling mechanisms. Round, shouldered-end tensile specimens, 6.41 ± 0.01 mm diameter with gauge length of 63.5 ± 0.1 mm were used for both load controlled cyclic loading and constant load, creep experiments.

Experimental Procedure

Load controlled cyclic loading and creep (constant load) experiments were conducted on a model TTC-M Instron machine. The tests were controlled by means of a Motorola M6809 computer. The test specimen and grip assembly were enclosed in an Instron temperature chamber, model 3111. The chamber had a long term temperature stability of ± 1.0°C. The temperature in the chamber was independently monitored with a thermometer placed near the specimen. During the experiment, the thermometer was read through the glass window of the chamber. For further details of the experimental procedure, references [11,26] can be consulted.

RESULTS AND DISCUSSION

Constitutive parameters

activation volume

The results of load controlled cyclic loading with a triangular load waveform and constant load creep experiments were used to evaluate the constitutive parameters A_f and V_f. Previous cyclic loading and stress relaxation experiments [10,11,26,27] showed that for the Zn-Al alloy, $H \approx 0$. Consequently, for the triangular load waveform, the integral in Eq. (11) was determined as [10]

$$\int_0^t \exp\frac{V_f(\tau_a - \tau_i)}{kT}dt = \frac{kTt}{V_f\tau_r}[\exp\frac{V_f(\tau_a - \tau_i)}{kT} - 1] \qquad (21)$$

Hence, the total strain is evaluated in function of time t = mp (where m is the number of cycles and p is the cycle period) and the stress amplitude as

$$\varepsilon = \varepsilon_0 + \frac{A_f kTt}{V_f \tau_r} \exp \frac{V_f(\tau_0 - \tau_i^o)}{kt} [\exp \frac{V_f \tau_r}{kT} - 1] \tag{22}$$

since at t = mp, $\tau_a - \tau_o = 0$. The steady state total strain rate then is

$$\dot{\varepsilon} = \frac{A_f kTt}{V_f \tau_r} \exp \frac{V_f(\tau_0 - \tau_i^o)}{kt} [\exp \frac{V_f \tau_r}{kT} - 1] \tag{23}$$

That is, during (constant amplitude) load controlled cyclic deformation, the steady state strain rate is constant and is a function of the initial effective shear stress and the stress amplitude.

The constitutive parameters were analyzed by plotting the steady state strain rate in function of the initial stress on a semi-logarithm scale as shown in Fig. 2. According to Eq. (23), the plot should be a straight line, the slope of which is proportional to the activation volume, V_f, while the intercept at $\tau_0 = 0$ is proportional to the parameter A_f and is a function of the stress amplitude and the internal stress level. However, for the Zn-Al alloy, the internal stress is negligibly small [8,10,11]. The constitutive parameters that were evaluated from constant load creep and cyclic loading experimental results are shown in Tables 1 and 2, respectively.

It is evident from Tables 1 and 2 that the constitutive parameters determined from the analysis of constant load (creep) and cyclic loading experimental results are identical. The equality of the constitutive parameters indicates the validity of the assumption that the material structural characteristics remain constant during cyclic deformation. Consequently, within the high stress and low temperature range where the rate of plastic flow can be approximated with activation over a single energy barrier, constant load (creep) experiments can be employed to determine the constitutive parameters and, by using the constitutive laws developed in this report, load controlled cyclic deformation behavior can be evaluated.

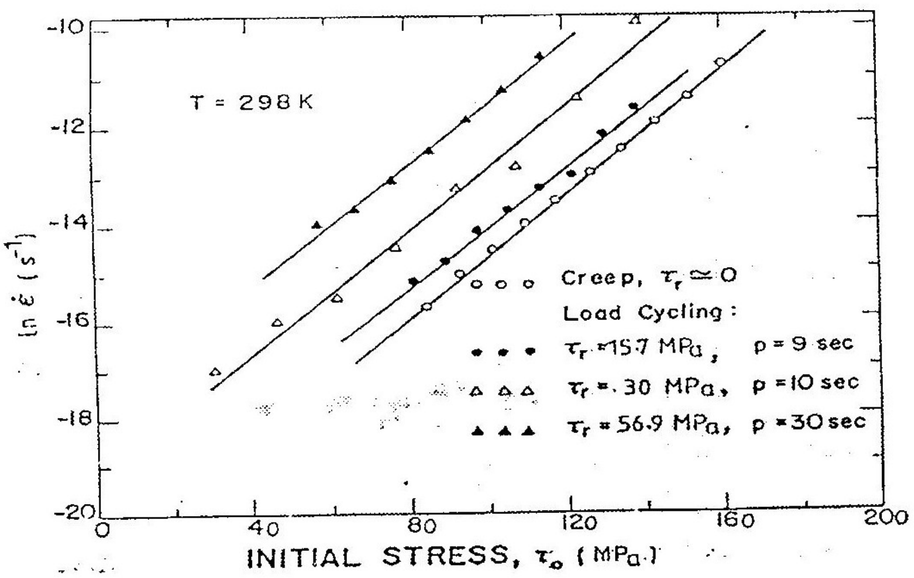

Fig. 2 The natural logarithm of strain rate plotted in function of the initial stres (The lines were obtained from least square method using Eqs. (16) and (23) for creep and cyclic loading, respectively. The symbols indicate the experimental data. For $\tau_r = 3.1$ kg/mm^2, each of the experimental points was determined from a different specimen while for the other stress amplitudes, a single specimen was used).

Table 1 Constitutive parameters determined from constant load experiments

Experiment No.	Temp. (K)	V_f (b^3)	λ_f (sec^{-1})
1	298	13	8.3×10^{-10}
2	317	13	$9. \times 10^{-9}$
3	330	13	6.42×10^{-8}
4	345	14	2.5×10^{-7}

Table 2 Constitutive parameters determined from load controlled cyclic loading experiments

Experiment No.	Temp (K)	τ_f (kg/mm^2)	V_f (b^3)	A_f (sec^{-1})
1	298	1.6	13	10^{-9}
2	298	3.1	14	7.8×10^{-9}
3	298	5.78	13	2.4×10^{-9}

Activation Energy

The activation energy associated with creep was determined from temperature cycling experiments and from Arrhenius plot. The rate of plastic flow was measured over the temperature range for which the activation energy was to be determined. It was assumed that within the temperature range the material structural characteristics ($\Delta G+$, ρ_m, and V_f) remain unchanged. That is, the material structural characteristics are constant during the activation energy measurements. When these conditions are satisfied, then it follows from Eq. (7) that, because the strain rates measured at two different temperatures T_1 and T_2 are related, the experimental apparent activation energy ΔG_f can be expressed from

$$\frac{\dot{\varepsilon}_{p1}}{\dot{\varepsilon}_{p2}} \approx \exp\left[-\frac{\Delta G_f}{k}\left(\frac{1}{T_1}-\frac{1}{T_2}\right)\right] \qquad (24)$$

or

$$\Delta G_f = -k\frac{d\ln\dot{\varepsilon}_p}{d\left(\frac{1}{T}\right)} \qquad (25)$$

Fig. 3 shows a typical strain versus time curve measured in a temperature cycling experiment. From the results of the test, the experimental activation energy was evaluated from Eq. (24). From the experimental results $\Delta G_f = 8.577 \times 10^3 k$, while the activation energy at zero stress was determined from eqs. (3) and (7) as $\Delta G_f = 0.964$ eV.

The experimental activation energy was also evaluated from the Arrhenius type plot using Eq. (25) (Fig. 4) leading to $\Delta G_f = 9.054 \times 10^3$ k with a correlation factor of 0.95.

Similarly, the activation energy ΔG^+_f at zero stress was determined as 0.956 eV.

The least square analysis of the arrhenius plot also leads to the evaluation of the parameter

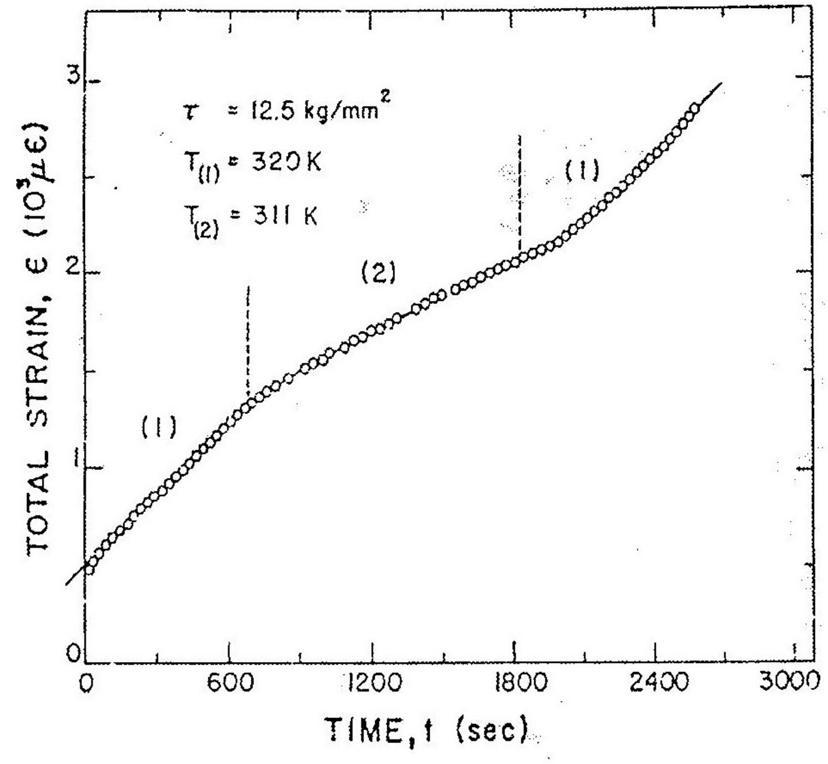

Fig. 3 A typical strain-time curve obtained from a temperature cycling experiment. The strain rate in region (1) was evaluated as 1.2×10^{-5}/sec. while that in region (2) is 5.53×10^{-6}/sec.

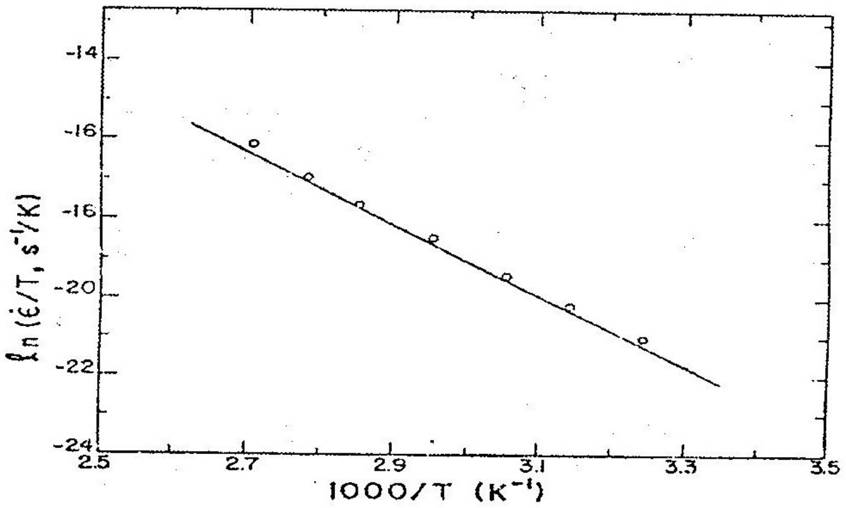

Fig. 4 The Arrhenius type plot for creep of the near eutectoid Zn-Al alloy (The experiments were carried out on a single specimen and at a constant shear stress of 8.15 kg/mm2. The steady state strain rate was measured in function of temperature which was increased in steps of about 10 K from 300 K to 370 K).

$$\frac{bl\bar{\rho}_m}{M} = 2x10^{-7}$$

which compares well with that determined from the analysis of the stress relaxation experimental results [12]. Table 3 shows the activation energy, ΔG^{+}_{f}, that was evaluated from the temperature change tests in creep and from stress relaxation. It is observed that the activation energy (for plastic flow of the near eutectoid zn-Al alloy) that was determined from the present analysis is comparable to that obtained by other investigators.

Comparative Analysis of Constitutive Parameters

In previous studies [10-12], the constitutive parameters for strain controlled cyclic deformation and stress relaxation were determined. The activation volume, V_f, for both stress relaxation and strain controlled cyclic deformation was determined as 17 ± $4b^3$ while the activation free energy, ΔG^{+}_{f} was 1.06 ± 0.02 eV. The present study shows that the activation volume, V_f, determined from load controlled cyclic loading and constant load (creep) experimental results is 13 ± $1b^3$ while the activation free

Table 3 Activated energy for plastic flow of the near eutectoid Zn-Al alloy

Testing Method	Method of Temperature Variation	Activation Energy ΔG_f(eV)	Investigators
Stress relaxation	Tests at different temperatures	1.06 ± 0.02	Mshana and Krausz |12|
Creep	Temperature cycling	0.964	Present study
Creep	Temperature change	0.956	Present study
Creep	Temperature change	1.09 ± 0.04	Chaudhari |29|
Creep	Temperature cycling	0.82 ± 0.05	Vaidya, Murty and Dorn |31|
Creep	Temperature change	0.82	Mohamed and Laangdon |30|

energy, ΔG_f, is 0.95 ± 0.01 eV. It is evident, therefore, that the material structural characteristics determined from stress relaxation, creep, load and strain controlled cyclic loading experimental results are identical. The conclusion that follows from this analysis is an important one: load and strain controlled cyclic deformations are different manifestations of the same basic process, depending on the control condition. The measured activation volume at room temperature for cyclic (strain and load controlled) deformation indicate that the process may be controlled by dislocation movement, either by Peierl's-Nabarro mechanism or by cross-slip mechanism [1]. A more detailed and definitive study would be outside of the scope of this report.

It is realized that for some materials, the variations of the structural characteristics during cyclic deformation may be significant. The mobile dislocation density may increase significantly due to dislocation multiplication and the activation volume may vary with the applied stress. For these materials, therefore, the variations of the structural characteristics must be incorporated in the development of the constitutive equations of cyclic loading.

CONCLUSIONS

It is concluded that cyclic deformation is a rate phenomenon, strongly dependent on the temperature and loading rate. Over the high stress and low temperature range where thermally activated plastic flow in cyclic (load and strain controlled) deformation can be approximated with activation over a single energy barrier, strain controlled cyclic deformation is essentially a stress relaxation process while load controlled cyclic deformation is a creep process. The material structural characteristics determined from stress relaxation, creep, load and strain controlled cyclic loading experimental results were identical, leading to the conclusion that load and strain controlled cyclic deformations are different manifestations of the same basic process, depending on the control condition. Consequently, it is recommended that stress relaxation and creep can be employed to determine the material structural characteristics which can then be used to predict the cyclic deformation behavior, using the constitutive laws developed in the present and previous [10-12] studies. However, the validity of the constitutive laws is limited to the stress, temperature, and time (or number of cycles) range where the rate of thermally activated plastic flow can be approximated with activation over a system of two consecutive energy barriers. It is also limited to cyclic deformation during which the mobile dislocation density remains constant. This limitation implies that the strain and stress amplitudes should be small, depending on the variation of the mobile dislocation density with stress or strain. For the Zn-Al alloy, however, the variations of the mobile dislocation density with stress or strain amplitudes and with number of cycles appears to be insignificant.

REFERENCES

1. A.S. Krausz and H. Eyring "Deformation Kinetics", Wiley-Interscience, New York, 1975.
2. U.F. Kocks, A.S. Argon, and M.F. Ashby "Thermodynamics and Kinetics of Slip", Pergamon Press Ltd., London, 1975.
3. A.S. Krausz and B. Faucher "A Kinetics Approach to the Derivation and Measurement of the Constitutive Equations of Time-dependent Deformation", Mechanical Testing for Deformation

Model Development, ASTM STP 765, R.W. Rhode and J.C. Swearengen, Eds., *American Society for Testing and Materials*, (1982), p.284

4. A.S. Krausz and B. Faucher "Energy Barrier Systems in Thermally Activated Plastic Flow", Reviews on the Deformation Behavior of Materials, P. Feltham, Ed., Vol. IV, No. 2, (1982).
5. M.J. Makin, "The Thermal Activation or Slip in Neutron Quadiated Copper", *Philosophical Magazine,* **9**, (1964), p. 81.
6. J. Weertman "Rate Processes in Plastic Deformation of Materials", Edited by J.C.M. Li and A.K. Mukherjee, A.S.M., Metal Park, Ohio, (1975).
7. D.H. Sastry, M. Luton and J.J. Jonas, "Thermally Activated Flow of HcP Metals at Low Temperatures", *Physical State of Solids*, **33a**, (1976). p.173
8. C.H. Laforce, A.S. Krausz and W. Ginman, "The Deformation Kinetics Analysis of Near Eutectoid Zn-Al Alloy", *Z. Metallkde*, **69**, (1978), p. 622.
9. B. Faucher "A Study of Steady State and Non-steady State Deformation Kinetics", Ph.D. Thesis, University of Ottawa, 1979.
10. J.S. Mshana and A.S. Krausz, "Rate Dependent Constitutive Equation of Cyclic Softening", *Z. Naturforsch.*, Vol. 40a, No. 7, p. 653 (1985).
11. J.S. Mshana and A.S. Krausz, "Constitutive Equation of Cyclic Softening", Trans. of ASME *Journal of Engineering Materials and Technology*, **107** (1), (1985), p. 7.
12. J.S. Mshana and A.S. Krausz, "Constitutive Equation of Plastic Deformation of a Zn-Al Alloy Under Tension - Tension Strain Controlled Cyclic Loading", *Mechanics of Materials*, **16**, (1987), p. 95.
13. H. Eyring, "Viscosity, Plasticity and Diffusion as Examples of Absolute Reaction Rates", *Journal of Chemical Physics*, **4**, (1936), p. 283.
14. E. Orowan, "On the Mobile Dislocation Density", *Proceedings of the Royal Society*, London, **52**, (1940), p. 8.
15. W.G. Johnston, "Effects of Mobile Dislocation Density on Internal Stress", *Journal of Applied Physics*, **33**, (1962), p. 2716
16. M. Klesnil and P. Lucas, Material Science Monoraphs, Vol. 7 "Fatigue of Metallic Materials", Elsevier Scientific Pub. Co., (1980).

17. A.S. Krausz, B.G. Craig, "Variable Stress Creep in Copper", *Acta Metallurgica*, **14**, (1966), p.1807.

18. O.H. Wyatt, Proc. Phys. "Transient Creep in Pure Copper", *Proceedings of the Physical Society* , **B66**, (1953), p. 459.

19. A. Neuhauser, N. Himstedt and Ch. Schwink, "Macroscopic and Microscopic Studies of the Plastic Deformation of Copper Single Crystals During Strain Rate Changes", *Phys. Stat. Sol.* (a) **3**, (1970), p. 585.

20. F. Guju, "The Influence of Internal Stress Fields on the Velocity of Dislocations", *Phys. Stat. Sol.*, **33**, (1969), p. 785.

21. U. Essmann, "Determination of Activation Volume in Low Temperature Creep", *Phys. Stat. Sol.*, **17**,(1966), p.725.

22. D.K. Shetty and M. Meshii, "Plastic Deformation of Aluminium Under Repeated Loading", *Met. Transactions*, **6A**, (1975), p. 349.

23. A.T. Price, J. "Cyclic Stress Retardationin Zn", *J. Institution of Metals*", **95**, (1966), p.87.

24. R. Koterazawa, "Cyclic Softening and Hardening of Metals", Proc. Int. Conf. on Creep and Fatigue in Elevated Temperature Applications, C 214/73, 214.1, Philadelphia, Sept. 1973.

25. R. Koterazawa, "Cyclic Softening and Hardening of Metals", Proc. Int. Conf. on Mechanical Behavior of Metals, III, Kyoto, Aug. 1971, p. 135.

26. J.S. Mshana "Rate Dependent Constitutive Equations of Cyclic Softening and Hardening", Ph.D. Thesis, University of Ottawa, 1986.

27. X. Zhu,B. Ramaswami "Fatigue Deformation of Superplastic Zn-22 Percent Al Eutectoid Alloy", Presented at the International Conference on Strength of Metals and Alloys (ICSME-7), Montreal, Canada, Aug. 1985.

28. A.S. Krausz, Z. W. Lian, J.S. Mshana, K. Krausz, "A Rate Theory Investigation of Cyclic Loading and Plastic Deformation in the High Stress and Ambient Temperature Range", Proceedings of the 15th Symposium of the International Committee on Aeronautical Fatigue, 21-23rd June, 1989, Jerusalem, Israel, pp. 185-197.

29. P. Chaudhari, "Deformation Behaviour of Superplastic Zn-Al Alloys", *Acta Met.*, **15**, (1967), p. 1777.

30. F.A. Mohamed and T.G. Langdon, "Determination of the Activation Energy for Superplastic Flow", *Phys. Stat. Sol.* 9(a), **33**,

(1976), p. 375.

31. M.L. Vaidya, K.L. Murty and J.E. Dorn, "High Temperature Deformation Mechanisms in Superplastic Zn-22% Al Eutectoid", *Acta Met.*, **21**, (1973), p. 1615.

The manuscript was received on 1st December 1994 and accepted for publication on 5th May 1995.