Biaxial Creep Deformation of Softened Celluloid under Variable Stresses*

By Hisaaki TOBUSHI**, Yutaka NARUMI*** and Kozi OSAWA****

Applying constant axial stress and variable torsional stress to a thin-walled tubular specimen of softened celluloid, creep deformation of the material was investigated. The main features obtained may be summarized as follows:

- (1) In tests with a variation in torsional stress, the axial creep strain shows transient softening just after the torsional stress change, and the rate of hardening of the material is continuous in the same stress state.
- (2) In cyclic torsional stress test, the torsional creep strain shows softening at the first reversal of torsional stress, while hardening of the material appears at the cyclic stress reversal and is saturated.
- (3) The viscous-viscoelastic theory may be applicable to creep deformation of the material under reversal and removal of stress by using the modification for the ratio of recoverable strain.

Key Words : Softened Celluloid, Creep Deformation, Multiaxial Stress State, Orientation Hardening, Viscous-Viscoelastic Model

1. Introduction

Microstructures of polymer and metal are different, but various similarities in macroscopic mechanical properties of these materials have been pointed out. Based on this fact, amorphous polymers are often used as the model materials to investigate the mechanical properties of metals like the case of the photoelastic method. However, in case that plastic and creep deformations are accompanied, because variation of internal state is related to that of microstructure of the material, it is necessary to take account of the history effect. In general, the difference in this effect between the model material and the actual one becomes significant in inelastic deformation. Furthermore, it is necessary to take account of effects of viscosity, volumetric strain and the particular characteristics of polymers, such as the glass transition temperature and the delayed yielding⁽¹⁾⁽²⁾.

On the other hand, with the recent development in synthesizing techniques of polymers, numerous kinds of polymers from soft elastomer to hard glassy material have come to be widely used for various purposes in wide field of industry. In addition, as machine elements are used under complex loadings at elevated temperature in many cases, correspondingly it has become important to study the mechanical properties of polymer precisely.

As for experimental investigations on

the mechanical properties of polymers, analyses of plastic and creep deformation behaviors have been developed as applications of the results of studies from the viewpoint of the fracture mechanics. However, most of these investigations are carried out under proportional loadings and a few of them are done under nonproportional loadings. Since the difference in mechanical properties due to difference of microstructures between the metal and the polymer may become more significant under nonsteady multiaxial stress states, it is necessary to study the mechanical properties of the polymer under this kind of loadings.

In the earlier works by the authors, a series of discussions from the viewpoint of the nonlinear viscoelastic theory were done on deformation behaviors of softened celluloid⁽³⁾⁻⁽⁵⁾.

In the present paper, as a basic work for investigating the creep deformation behaviors under multiaxial stress states, creep deformations were studied under various combinations of two stress components. That is, the creep deformation behavior of a thin-walled tube of softened celluloid was investigated by applying several combinations of constant axial tensile stress and torsional stress added to and from stepwise. The representation of the creep deformation was discussed from the viscous-viscoelastic theory by Findley and his co-workers which was discussed for prediction of creep deformation under a simple stress trajectory⁽⁶⁾.

2. Specimen and experimental procedure

2.1 Specimen

The specimen used was a thin-walled tube of celluloid softened by heating in an oil bath at 65°C. The nominal outside diameter and the wall thickness were 50 and 3

* Received 10th October, 1983.

** Associate Professor, Aichi Institute of Technology(Yagusacho, Toyota, Japan).

*** Professor, Aichi Institute of Technology(Yagusacho, Toyota, Japan).

**** Research Engineer, Nidek Co., Ltd. (Hiroishicho, Gamagori, Japan).

mm, respectively, the same as in the previous paper⁽⁴⁾. Young's modulus and proportional limit of the material at an experimental temperature were 1088 and 6.5 MPa, respectively.

2.2 Experimental procedure

The experimental apparatus and procedure were the same as in the previous paper⁽⁴⁾.

Table 1 Experimental conditions

Exp. No.	stage (min)	1		2		3		4		θ deg
		σ	τ	σ	τ	σ	τ	σ	τ	
A	A-1	294	170	294	-170	294	170	294	-170	$\pm 45^\circ$
	A-2	334	198	334	-198	334	198	334	-198	
	A-3	412	283	412	-283	412	283	412	-283	
B	B-1	245	245	245	-245	245	245	245	-245	$\pm 60^\circ$
	B-2	294	294	294	-294	294	294	294	-294	
	B-3	343	343	343	-343	343	343	343	-343	
C	C-1	294	0	294	170	294	294	294	0	$0^\circ, 45^\circ, 60^\circ$
	C-2	343	0	343	198	343	343	343	0	

Table 2 Experimental conditions of calibration test

Exp. No.	time stage	0 ~ 150 min		150 ~ 300 min	
		σ MPa	τ MPa	σ MPa	τ MPa
X-1		3.92	0	0	0
X-2		4.90	0	0	0
X-3		5.88	0	0	0
X-4		6.86	0	0	0
Y-1		0	2.38	0	0
Y-2		0	2.83	0	0
Z-1		3.43	1.97	0	0
Z-2		4.81	2.78	0	0

(a) Exp. A ($\theta = \pm 45^\circ$), Exp. B ($\theta = \pm 60^\circ$)

(b) Exp. C ($\theta = 0^\circ, 45^\circ, 60^\circ$)

Fig. 1 Stress trajectory

In this experiment, as shown in Table 1 and Fig. 1, creep deformation was measured by applying combination of a constant axial tensile stress σ and a varying torsional stress τ with an interval, 90 min. That is, in Exp. A ($\theta = \pm 45^\circ$) and in Exp. B ($\theta = \pm 60^\circ$), a constant σ and a cyclic τ with the same amplitude were applied. In Exp. C ($\theta = 0^\circ, 45^\circ, 60^\circ$), a constant σ and a τ with step-wise increase followed by removal were applied. Where, θ denotes the angle between the stress vector and the σ -axis in the deviatoric stress plane. Torsional stress τ was varied instantaneously every 90 min. As calibration test for the viscous-viscoelastic theory, creep tests were performed under stress conditions of constant stress followed by removal as shown in Table 2.

3. Experimental results and discussions

3.1 Axial strain

Experimental results of the axial strain ϵ versus time t in Exp. A and Exp. C are shown in Fig. 2 using various symbols. When torsional stress varies under a constant axial stress, the resistance to the axial deformation decreases just after variation in torsional stress and the axial strain rate increases, that is, transient softening occurs. The magnitude of strain hardening at each stage under constant stress state depends on the torsional stress level. In the stages of the same stress state, for example, stage 1 and stage 3 or stage 2 and stage 4 of Exp. A [Fig. 2(a)] and stage 1 and stage 4 of Exp. C [Fig. 2(b)], as shown in Fig. 3, the axial strain rate changes continuously

(a) Exp. A

(b) Exp. C

Fig. 2 Relation between ϵ and t

from the former to the latter stages except in the transient softening range just after the variation of torsional stress.

This may be explained as follows. Since the strain hardening in polymers occurs by effects that molecular chains of noncrystalline region are stretched and oriented in the direction of the principal stress and some parts of them are crystallized⁽⁷⁾⁻⁽⁹⁾, these orientation hardening and cross-links in the crystallized region do not disappear easily. Thus, the anisotropic hardening dependent on the orientation would occur.

3.2 Torsional strain

The relations between the torsional strain γ and time t in Exp. A and Exp. C are shown in Fig. 4 using various symbols. As shown in Fig. 4(a) for test with reversal in torsional stress, variation of γ in stage 2 is larger than that in other stages. These relations between variation of the torsional creep strain in each stage $|\Delta\gamma^c|$ and the number of stages are shown in Fig. 5. The magnitude of $|\Delta\gamma^c|$ in stage 2 under the first stress reversal is about 1.2 through 1.6 times larger than that in stage 1. This phenomenon seems similar to the Bauschinger effect and occurs by effects that the orientation in microstructure caused by deformation in stage 1 decreases the resistance to deformation in the opposite direction and the recoverable strain component after stress removal is large ($R = 0.815$) as shown in the latter section (§ 4.2). However, after stage

3, $|\Delta\gamma^c|$ decreases under cyclic reversals of torsional stress and tends to saturate a certain value. This phenomenon shows the same tendency as observed in the previous paper⁽¹⁰⁾. That is, the torsional strain range increases in the early several cycles of reversal in torsional stress and, after these cycles, decreases with the number of cycles.

According to Fig. 4(b) for Exp. C with stepwise increase and removal of torsional stress, the creep strain rate in stage 3 is larger than that in stage 2. The recoverable strain rate in stage 4 is small and the recoverable strain is far smaller than the creep strain in stages 2 and 3.

3.3 Creep strain trajectory

The creep strain trajectories in the deviatoric strain plane ($\epsilon^c, \gamma^c/\sqrt{3}$) consisted of the axial creep strain ϵ^c and the torsional one $\gamma^c/\sqrt{3}$ for Exps. A-3 and B-2 and Exp. C are shown in Fig. 6 with the stress vector for each test. In stage 1, directions of the stress vector and of the creep strain increment vector almost coincide. When the torsional stress varies, direction of the creep strain increment vector tends to show that of the torsional stress component (stress increment vector) against that of the stress vector. However, direction of the creep strain increment vector approaches that of the stress vector with an increase of the creep deformation. The relations between the angle of delay of the creep increment vector against the stress vector $\Delta\theta$ and the arc length of the

Fig. 3 Axial strain at the stages with the same stress state

(a) Exp. A

(b) Exp. C

Fig. 4 Relation between γ and t

creep strain trajectory $\Delta\epsilon^c$ at each stage for Exps. A and B are shown in Fig. 7. From the figure, in stage 2 under the first variation of the torsional stress, $\Delta\theta$ decreases to 0° for 90 min. However, in the following stages 3 and 4, $\Delta\epsilon^c$ becomes short and $\Delta\theta$ does not decrease sufficiently for 90 min. In case of the high stress level, it takes a long $\Delta\epsilon^c$ for $\Delta\theta$ to decrease.

4. Formulation by viscous-viscoelastic theory

4.1 Viscous-viscoelastic theory Creep strain of polymers and metals un-

Fig. 5 Relation between $|\Delta\gamma^c|$ and the number of stages

(a) Exp. A-3, B-2

(b) Exp. C

Fig. 6 Creep strain trajectory

der various stress states at elevated temperature is well described by the viscous-viscoelastic (VV) theory and its modified theory by Findley and his co-workers⁽¹¹⁾⁻⁽¹⁵⁾.

In the VV theory, strain is resolved into five components :

$$\epsilon_{ij} = \epsilon_{ij}^e + \epsilon_{ij}^p + \epsilon_{ij}^v(\text{pos}) + \epsilon_{ij}^v(\text{neg}) + \epsilon_{ij}^{\text{ve}} \quad (1)$$

where, ϵ_{ij}^e , ϵ_{ij}^p , ϵ_{ij}^v and $\epsilon_{ij}^{\text{ve}}$ represent elastic, plastic, time-dependent nonrecoverable viscous with positive and negative components and time-dependent recoverable viscoelastic strain, respectively.

Under constant stress, if time-dependent strain is represented by the power function of time, the powers of ϵ_{ij}^v and $\epsilon_{ij}^{\text{ve}}$ coincide and the ratio R of $\epsilon_{ij}^{\text{ve}}$ to ϵ_{ij}^v is constant,

Eq. (1) may be expressed as follows:

$$\epsilon_{ij} = \epsilon_{ij}^e + \epsilon_{ij}^p + M_{ij}t^N + b_{ij}t^n = \epsilon_{ij}^e + M_{ij}(1+R)t^n \quad (2)$$

where, $\epsilon_{ij}^e = \epsilon_{ij}^e + \epsilon_{ij}^p$, $M_{ij}t^N = \epsilon_{ij}^v$, $b_{ij}t^n = \epsilon_{ij}^{\text{ve}}$, $N = n$, $R = b_{ij}/M_{ij}$.

Let us consider the first three terms of a multiple integral representation which is simplified to a single integral one by means of the modified superposition principle and represent ϵ_{ij}^e and $M_{ij}(1+R)$ in Eq. (2) by use of these ϵ_{ij}^e functions. In the single integral simplification, the third-order representation yields the following expression for axial strain ϵ_{11} and torsional one ϵ_{12} resulting from constant combined axial stress σ and torsional one τ of an isotropic

(a) Exp. A

(b) Exp. B

Fig. 7 Relation between $\Delta\theta$ and $\Delta\epsilon^c$

material,

$$\epsilon_{11} = F_1\sigma + F_2\sigma^2 + F_3\sigma^3 + F_4\sigma\tau^2 + F_5\tau^2 \dots (3)$$

$$\epsilon_{12} = G_1\tau + G_2\tau^3 + G_3\sigma\tau + G_4\sigma^2\tau \dots (4)$$

where, the creep functions F_i and G_i are given as follows:

$$F_i = F_i^0 + F_i^+ t^n, \quad (i = 1, \dots, 5) \dots (5)$$

$$G_i = G_i^0 + G_i^+ t^n, \quad (i = 1, \dots, 4) \dots (6)$$

The coefficients F_i^0 , F_i^+ , G_i^0 and G_i^+ are the material constants at test temperature and the first terms in the right hand side of Eqs. (5) and (6) correspond to the strain which appears instantaneously under the stress variation and the second terms do to the creep strain.

The stress - strain relation is obtained by Eq. (2) employing Eqs. (3) through (6). The strain hardening theory and a modified superposition principle are employed for representations of viscous strain ϵ_{ij}^v and viscoelastic one ϵ_{ij}^{ve} , respectively.

4.2 Application to experimental results

Using the experimental results of the calibration tests X, Y and Z, and stage 1 in Exps. A, B and C, the coefficients n , R , F_i^0 , F_i^+ , G_i^0 and G_i^+ in the VV theory were determined.

The results obtained by the calibration tests are shown in Table 3. The coefficient ϵ_{ij}^+ denotes the coefficient $M_{ij}(1+R)$ which represents the time-dependent strain in Eq.

Table 3 Values of constants in the theory by the calibration test

Exp.No	ϵ_{11}		ϵ_{12}		σ		τ	
	n	R	n	R	$\times 10^{-3} \text{ MPa}$	$\times 10^{-3} \text{ MPa}$	$\times 10^{-3} \text{ MPa}$	$\times 10^{-3} \text{ MPa}$
X-1	0.401	0.872	—	—	2.97	3.92	—	—
X-2	0.404	0.851	—	—	3.40	4.90	—	—
X-3	0.406	0.795	—	—	5.07	5.88	—	—
X-4	0.409	0.477	—	—	6.48	6.86	—	—
Y-1	—	—	0.432	0.776	—	—	2.30	2.38
Y-2	—	—	0.407	0.494	—	—	5.41	2.83
Z-1	0.386	0.766	0.401	0.831	2.10	3.43	2.84	1.97
Z-2	0.395	0.286	0.408	0.238	8.90	4.81	12.1	2.78

Table 4 Values of the material constants

$F_1^0 = 9.19 \times 10^{-4} \text{ MPa}^{-1}$	$G_1^0 = 1.38 \times 10^{-3} \text{ MPa}^{-1}$
$F_2^0 = F_3^0 = F_4^0 = F_5^0 = 0$	$G_2^0 = G_3^0 = G_4^0 = 0$
$F_1^+ = 1.00 \times 10^{-3} \text{ MPa}^{-1} \cdot \text{min}^{-n}$	$G_1^+ = 2.38 \times 10^{-4} \text{ MPa}^{-1} \cdot \text{min}^{-n}$
$F_2^+ = -1.35 \times 10^{-4} \text{ MPa}^{-2} \cdot \text{min}^{-n}$	$G_2^+ = 7.05 \times 10^{-5} \text{ MPa}^{-2} \cdot \text{min}^{-n}$
$F_3^+ = 1.84 \times 10^{-5} \text{ MPa}^{-3} \cdot \text{min}^{-n}$	$G_3^+ = 7.80 \times 10^{-5} \text{ MPa}^{-2} \cdot \text{min}^{-n}$
$F_4^+ = 4.32 \times 10^{-5} \text{ MPa}^{-3} \cdot \text{min}^{-n}$	$G_4^+ = 1.59 \times 10^{-5} \text{ MPa}^{-3} \cdot \text{min}^{-n}$
$F_5^+ = 0$	
note $n=0.405$ $R=0.815$ $\nu=0.5$	

(2), and each value in the table was determined from the experimental data by using least squares. Taking all tests into account, the average value of $n = 0.405$ was yielded. Eliminating the data of R obtained in tests X-4, Y-2 and Z-2, the average of $R = 0.815$ was obtained. Values of ϵ_{ij}^+ in Table 3 and those in stage 1 in Exps. A, B and C calculated by using the value of $n = 0.405$ are plotted by various symbols in Fig. 8. Making the calculations, the values of F_i^+ and G_i^+ shown in Table 4 were obtained. The calculated results are shown by the curves in Fig. 8. As shown in the figure, the experimental data are well predicted by the VV theory.

The calculated results by the VV theory for Exps. A and C are shown by solid curves in Figs. 2 and 4, respectively.

Torsional strain affected directly by the variation in torsional stress is well

(a) $\epsilon_{11}^+ - \sigma$ relation

(b) $\epsilon_{12}^+ - \tau$ relation

Fig. 8 Relation between the coefficient ϵ_{ij}^+ and stress

predicted by the VV theory for both Exp. A [Fig. 4(a)] and Exp. C [Fig. 4(b)].

However, for axial strain shown in Fig. 2(a), the transient softening phenomena due to the torsional stress reversal after stage 2 are not predicted by the VV theory. Furthermore, for axial strain shown in Fig. 2(b), though the creep deformation under loading process till stage 3 is well predicted by the VV theory, in stage 4 after the torsional stress removal, the experimental data of axial strain increases but the theoretical one recovers. Thus, axial creep strain under the torsional stress reversal or removal is not predicted by the VV theory.

4.3 Considerations on axial strain

As discussed in the preceding section, axial creep after the torsional stress reversal or removal under constant axial stress is not well described by the VV theory. Findley and his co-workers modified the strain under the stress reversal or removal by using the creep limit σ^* and τ^* for 2618 aluminum alloy under multiaxial variable stress at elevated temperature. However, even if the modified theory is em-

ployed, it is difficult for the viscoelastic material to determine the definite values of σ^* and τ^* . Furthermore, in order to describe the increase of axial strain after the removal of torsional stress, it is necessary to take the variation of σ^* and τ^* due to anisotropic hardening of creep into account. Thus, the phenomena could not be expressed simply.

The relation between creep strain ϵ_{ij}^c and recoverable strain ϵ_{ij}^r in the calibration test is shown in Fig. 9. The ratio of ϵ_{ij}^r to ϵ_{ij}^c decreases with growth of ϵ_{ij}^c as same as in the case of metal at elevated temperature⁽¹⁶⁾. As the strain is calculated by using the superposition principle, an increase of strain accompanied with softening which is caused by a change in stress may be predicted by the restraint of recoverable strain. This restraint may be achieved under the condition that the ratio R which describes the recoverable strain is smaller than an assumed constant value. Using the above-mentioned condition for the m -step stress variation, axial viscoelastic strain ϵ_{11}^{ve} will be given as follows:

$$\begin{aligned} \epsilon_{11}^{ve} = & \frac{R_1}{1+R_1} \{F(\sigma_1, \tau_1)t_1^n + F(\sigma_2, \tau_2)(t-t_1)^n + \dots + F(\sigma_{m-1}, \tau_{m-1})(t-t_{m-2})^n + F(\sigma_m, \tau_m)(t-t_{m-1})^n\} \\ & - \frac{R_m}{1+R_1} \{F(\sigma_1, \tau_1)(t-t_1)^n + F(\sigma_2, \tau_2)(t-t_2)^n + \dots + F(\sigma_{m-1}, \tau_{m-1})(t-t_{m-1})^n\} \\ & + \frac{R_2-R_1}{1+R_1} F(\sigma_1, \tau_1)(t_2-t_1)^n + \frac{R_3-R_2}{1+R_1} \{F(\sigma_1, \tau_1)(t_3-t_1)^n + F(\sigma_2, \tau_2)(t_3-t_2)^n\} + \dots \\ & + \frac{R_m-R_{m-1}}{1+R_1} \{F(\sigma_1, \tau_1)(t_{m-1}-t_1)^n + F(\sigma_2, \tau_2)(t_{m-1}-t_2)^n + \dots + F(\sigma_{m-2}, \tau_{m-2})(t_{m-1}-t_{m-2})^n\} \\ & t > t_{m-1}, \dots \dots \dots (7) \end{aligned}$$

where, the stress states (σ, τ) and the ratio R at time t are: σ_1, τ_1, R_1 for $0 < t < t_1$; σ_2, τ_2, R_2 for $t_1 < t < t_2$; $\dots$; σ_m, τ_m, R_m for $t > t_{m-1}$ and R_1 is determined by the calibration test. In the right hand side of Eq. (7), the first and second terms represent the superposed relations using the ratio R_m and the remaining terms are the correction terms at each stage. In the case without the torsional stress removal or reversal, the ratio $R_m = R_1$ in all stages and it needs no correction.

As shown in Fig. 6(a), when the absolute value $|\gamma^c/\sqrt{3}|$ of torsional creep strain in the preceding stage followed by the tor-

sional stress reversal is large, the axial creep strain increment $\delta\epsilon^c$ in the following stage becomes large. So, it may be assumed that the ratio R_m is represented by the simple relation of $|\gamma^c|$. The relations between the ratio R_m for axial strain obtained by Eq. (7) and the absolute value $|\gamma^c|$ of torsional creep strain in the preceding stage followed by a change in torsional stress are shown in Fig. 10 using various symbols. In the case without torsional strain, there does not appear the effect of $|\gamma^c|$. Thus, the experimental results may be represented by the following line drawn through the point $R_1 (= 0.815)$ for $|\gamma^c| = 0$:

Fig. 9 Relation between ϵ_{ij}^c and ϵ_{ij}^r

Fig. 10 Relation between R_m and $|\gamma^c|$

$$R_m = R_1 - a|\gamma^c|,$$

$$(R_1 = 0.815, a = 9.7) \dots\dots\dots(8)$$

Thus, axial strain followed by the torsional stress removal or reversal is obtained by applying Eq. (8) to Eq. (7). Axial strain calculated in the above-mentioned way is shown with the broken curve in Fig. 2. As seen from the figure, the experimental results are well described.

5. Conclusions

Applying combinations of constant axial stress with reversal, stepwise increase or removal of torsional stress to a thin-walled tube of celluloid softened by heating, the creep deformation behaviors were investigated. The results may be summarized as follows:

- (1) When axial stress is kept constant and torsional stress is varied, axial creep strain in the stages with the same state of stress vector shows continuous hardening except for the phenomenon of transient softening.
- (2) In case of cyclic torsional stress reversal, the amount of torsional creep strain variation increases under the first reversal but decreases under the following reversals.
- (3) In the deviatoric strain plane, the direction of creep strain increment vector inclines to that of stress increment vector just after the stress variation but approaches that of stress vector with the growth of creep strain.
- (4) The behaviors of strain due to the corresponding variable stress component are well described by the viscous-viscoelastic theory by Findley and his co-workers, but the effect of the torsional stress removal or reversal upon axial strain is not predicted. However, using the ratio R_m which describes the recoverable level of the viscoelastic strain, the above-mentioned effect is well described by the theory.

Acknowledgements

The authors are grateful to Dr. Y. Ohashi, Professor of Nagoya University for his valuable advice and to students of Aichi Institute of Technology for performing the experiments.

References

- (1) Bender, M. F. and Williams, M. L., J. Appl. Phys., 34 (1963), 3329.
- (2) Narisawa, I., et al., J. Polym. Sci. Phys., 16 (1978), 1459.
- (3) Ohashi, Y. and Tobushi, H., Bull. JSME, 18-121 (1975), 656.
- (4) Ohashi, et al., Trans. Japan Soc. Mech. Engrs. (in Japanese), 42-364 (1976), 3744.
- (5) Tobushi, H., et al., Bull. JSME, 24-188 (1981), 314.
- (6) Tobushi, H., et al., Proc. 20th Japan Cong. Materials Research, 20 (1982), 266.
- (7) Nielsen, L. E., Mechanical Properties of Polymers, (1962), Reinhold Pub..
- (8) Ferry, J. D., Viscoelastic Properties of Polymers, 3rd Ed., (1980), 224, John Wiley & Sons.
- (9) Aklonis, J. J. and MacKnight, W. J., Introduction to Polymer Viscoelasticity, 2nd Ed., (1983), 102, John Wiley & Sons.
- (10) Tobushi, H., et al., Bull. JSME, 27-233 (1984), 2323.
- (11) Findley, W. N. and Lai, L. S., Trans. ASME, J. Appl. Mech., 45 (1978), 507.
- (12) Lai, J. S. and Findley, W. N., Trans. ASME, J. Appl. Mech., 47 (1980), 21.
- (13) Cho, V. W. and Findley, W. N., Trans. ASME, J. Appl. Mech., 47 (1980) 755.
- (14) Findley, W. N. and Lai, L. S., Trans. ASME, J. Appl. Mech., 48 (1981), 47.
- (15) Cho, V. W. and Findley, W. N., Trans. ASME, J. Appl. Mech., 49 (1982), 297.
- (16) Yagi, K., et al., J. Soc. Materials Sci. Japan (in Japanese), 27-301 (1978), 35.