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Creep of Mild Steel under Periodic Stresses of Rectangular Wave*

(III) Prediction of the Creep Deformation under Periodic Stresses

By Shuji TAIRA**, Kichinosuke TANAKA***,
and Kiyotsugu OHJI****

In the preceding paper, it was clarified that the deformation of mild steel subjected to an unsymmetrical stress wave could not be predicted by the mechanical equation of state in solid, which was often called the strain hardening theory, while the deformation under a symmetrical stress wave could be predicted by it. The purpose of this paper is to establish a method of predicting the deformation under unsymmetrical periodic stresses as well as the deformation under symmetrical periodic stresses. The deformation was predicted by the authors' theory of deformation, which explained the behavior of material at any instant from the viewpoint of the integrated effect of work hardening and recovery, which the material had experienced before. It is concluded that prediction by this method is considerably good in any case of rectangular stress wave.

1. Introduction

In the two preceding papers⁽¹⁾⁽²⁾, the authors have reported experimental work on creep deformation of mild steels under periodic stresses of rectangular wave. The influences of unsymmetry of fundamental stress-time patterns, period of stress wave and the magnitudes of applied stresses on deformation were mainly studied in those paper. The

experimental results were also examined from the viewpoint of possibility of prediction of deformation by the mechanical equation of state in solid⁽³⁾ (or often called the strain hardening theory) using the information of the constant stress creep tests. It has been found that, under certain stress-time patterns such that the ratio of the time under the stresses higher than the mean stress to that under the stresses lower than the mean stress is much smaller than unity, the prediction of strain by the mechanical equation of state gives the strain on dangerous side, while it coincides well with the experimental results when the ratio is larger than unity.

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** Professor, Faculty of Engineering, Kyoto University.

*** Assistant Professor, Faculty of Engineering, Kyoto University.

**** Assistant Professor, Faculty of Engineering, Osaka University, Miyakojima-ku, Osaka.

On the other hand, the authors have developed a theory of plastic deformation of metals at high temperatures^{(2),(4)~(6)} and have applied it to some cases such as high temperature tensile test at constant strain rate⁽⁵⁾, constant stress creep test⁽⁵⁾ and creep test under stepwise changing stress⁽⁶⁾⁽²⁾. As a result it has been concluded that this theory may be applicable for prediction of deformation of the metallographically stable materials at high temperatures.

In the present paper, the authors intend to apply the theory to more complicated cases such as creep test under periodic stresses of rectangular wave, in which the prediction of deformation by the mechanical equation of state is not applicable, and to establish a method to predict the deformation in such cases.

The systematic researches on the creep under varying stresses have not progressed so far because of its complicatedness in actuality. J.E. Dorn and his collaborators have published some papers⁽⁷⁾ on this subject, and have proposed a parameter representing the state of materials which have experienced some stress history. J. D. Lubahn has reported an idea⁽⁸⁾ to discuss stress history in his paper on evaluation of the prediction by the mechanical equation of state. Some other fundamental researches are also found, but are far from completion from the standpoint of prediction of deformation. Although these researches will make progress and might contribute in future to the prediction of deformation under any conditions, it may be said that there is no reliable method to predict quantitatively the deformation under any conditions up to date.

2. Symbols

The same symbols used in the preceding report⁽²⁾ are also used in this paper. The symbols for stress-time patterns, stress ranges and combinations of experimental conditions were shown in Fig. 1, Tables 1 and 4 of the preceding paper⁽²⁾ respectively. The symbols for the materials shown in Table 2 of the paper⁽²⁾ are also used in this paper. The symbols of variables used in this paper are as follows.

Stress: kg/mm²

σ : applied stress

$\sigma_{\max}$: maximum applied stress

$\sigma_{\min}$: minimum applied stress

$\sigma_m = (\sigma_{\max} - \sigma_{\min})/2$: mean stress

σ_0 : applied stress before the stress change, or applied stress before the first stress change

σ_1 : applied stress after the stress change, or applied stress during the first to the second

stress changes

σ_n : applied stress during the n th to the $(n+1)$ th stress changes

$\Delta\sigma$: magnitude of step of a stress change

$\bar{\sigma}$: internal yield stress

$\bar{\sigma}_0$: initial value of internal yield stress

$\bar{\sigma}_1$: internal yield stress just before the stress change, or internal yield stress just before the first stress change

$\bar{\sigma}_{1+}$: internal yield stress immediately after the stress change, or internal yield stress immediately after the first stress change

$\bar{\sigma}_n$: internal yield stress just before the n th stress change

$\bar{\sigma}_{n+}$: internal yield stress immediately after the n th stress change

$(\partial\bar{\sigma})_0 = \bar{\sigma}_{1+} - \bar{\sigma}_1$: difference in internal yield stresses immediately after and just before the stress change, i.e. instantaneous hardening for $(\partial\bar{\sigma})_0 > 0$ and instantaneous softening for $(\partial\bar{\sigma})_0 < 0$

Time : min

p : period of stress wave

t : time, or time after the start of test

t_l : elapsed time after the stress change

$\bar{t}$: total time under maximum stress $\sigma_{\max}$

τ : time under maximum stress in one cycle

Strain : %

ϵ : strain

ϵ_1 : strain just before the stress change

ϵ_0 : initial instantaneous strain in the constant stress creep test

ϵ_{01} : initial instantaneous strain for applied stress σ_1

ϵ_c : creep strain produced under the applied stress σ_0 before the stress change

ϵ_{cs} : strain in the constant stress creep test

ϵ_{vs} : strain in the varying stress creep test

Strain rate : %/min

$f(\bar{\sigma}, \sigma, T)$: strain rate function

$\dot{\epsilon}$: strain rate

$\dot{\epsilon}_1$: strain rate just before the stress change

Others :

$(\partial\bar{\sigma}/\partial\epsilon)'$: coefficient of work hardening in kg/mm²/%

$(\partial\bar{\sigma}/\partial t)'$: rate of recovery in kg/mm²/min

$(\partial\bar{\sigma}/\partial t)' = (\partial\bar{\sigma}/\partial t)''$, either when the stress change is absent, or after the stress increases. $(\partial\bar{\sigma}/\partial t)' = (\partial\bar{\sigma}/\partial t)'' + (\partial\bar{\sigma}/\partial t_l)'$, after stress reduction

$(\partial\bar{\sigma}/\partial t)_1'$: rate of recovery just before the stress change in kg/mm²/min

$(\partial\bar{\sigma}/\partial t)''$: a portion of rate of recovery depending on $\bar{\sigma}$, σ and T in kg/mm²/min

$(\partial\bar{\sigma}/\partial t_l)'$: a portion of rate of recovery depending on t_l in addition to $\bar{\sigma}$, σ and T in kg/mm²/min

$$F \equiv 1/[(\partial \bar{\sigma}/\partial \epsilon)' + (\partial \bar{\sigma}/\partial t)'] f(\bar{\sigma}, \sigma, T) :$$

strain increment per unit increase in
internal yield stress in %/kg/mm²

1/F : coefficient of effective work hardening in
kg/mm²/%

R : generalized gas constant, 1.987 cal/mol °K

T, T₀ : absolute temperatures in °K

τ/p : ratio of time under maximum stress to
period in %

The units above mentioned should be used for
all expressions in this paper.

3. Method of calculation of strain under stepwise changing stresses and the characteristic functions

3.1 Extension of the authors' fundamental equation of deformation⁽⁴⁾

In the preceding report⁽⁴⁾, the case when F or $1/F$ is expressed as functions of $\bar{\sigma}$, σ and T , being independent of t_i , has been treated. In the present paper, this method is applied to the case when F depends on t_i in addition to $\bar{\sigma}$, σ and T .

In the case where F is dependent on $\bar{\sigma}$, σ and T , the strain under stepwise varying stress is calculated by the equations⁽⁴⁾,

$$\epsilon = \int_{\bar{\sigma}_0}^{\bar{\sigma}_1} F(\bar{\sigma}, \sigma_0, T_0) d\bar{\sigma} + \int_{\bar{\sigma}_1}^{\bar{\sigma}_2} F(\bar{\sigma}, \sigma_1, T_0) d\bar{\sigma} \\ + \dots + \int_{\bar{\sigma}_{n-1}}^{\bar{\sigma}} F(\bar{\sigma}, \sigma_{n-1}, T_0) d\bar{\sigma}, \quad d\epsilon \geq 0 \quad (1)$$

$$t = \int_{\bar{\sigma}_0}^{\bar{\sigma}_1} \frac{F(\bar{\sigma}, \sigma_0, T_0)}{f(\bar{\sigma}, \sigma_0, T_0)} d\bar{\sigma} + \int_{\bar{\sigma}_1}^{\bar{\sigma}_2} \frac{F(\bar{\sigma}, \sigma_1, T_0)}{f(\bar{\sigma}, \sigma_1, T_0)} d\bar{\sigma} \\ + \dots + \int_{\bar{\sigma}_{n-1}}^{\bar{\sigma}} \frac{F(\bar{\sigma}, \sigma_{n-1}, T_0)}{f(\bar{\sigma}, \sigma_{n-1}, T_0)} d\bar{\sigma} \quad (2)$$

In these equations, the internal yield stress just before the stress change is assumed to be equal to the one immediately after the stress change. When a difference exists between the two, we can calculate the strain by changing only the lower limits of integrals in Eqs. (1) and (2) from $\bar{\sigma}_1$, $\bar{\sigma}_2, \dots, \bar{\sigma}_{n-1}$ to $\bar{\sigma}_{1+}$, $\bar{\sigma}_{2+}, \dots, \bar{\sigma}_{n-1+}$ respectively.

When F depends on t_i besides $\bar{\sigma}$, σ and T , however, the deformation can not be calculated, because Eqs. (1) and (2) are not of variable separable type. In such cases, the deformation may be computed numerically using the next fundamental equations⁽⁴⁾,

$$d\bar{\sigma} = (\partial \bar{\sigma}/\partial \epsilon)' d\epsilon + (\partial \bar{\sigma}/\partial t)' dt \quad (3)$$

$$d\epsilon = f(\bar{\sigma}, \sigma, T) dt \quad (4)$$

$$\text{or } d\bar{\sigma} = [(\partial \bar{\sigma}/\partial \epsilon)' + (\partial \bar{\sigma}/\partial t)'] f(\bar{\sigma}, \sigma, T) d\epsilon \\ = 1/F \cdot d\epsilon \quad (5)$$

Given a sufficiently small increment of time dt , $d\epsilon$ and $d\bar{\sigma}$ would be determined by combination of Eqs. (3) and (4) or (4) and (5), if F were

known. By successive applications of this procedure, a numerical value of deformation may be obtained. In this place, $1/F$ can be determined following Eq. (5), if the expressions of characteristic functions $f(\bar{\sigma}, \sigma, T)$, $(\partial \bar{\sigma}/\partial \epsilon)'$ and $(\partial \bar{\sigma}/\partial t)'$ are known.

$1/F$ for use in calculation of deformation under stepwise varying stresses is also obtainable from the data of constant stress creep tests. When $f(\bar{\sigma}, \sigma, T)$ is known, $\dot{\epsilon}$ - ϵ relation in constant stress creep test is transformed into $\bar{\sigma}$ - ϵ relation. Then differentiating this with respect to ϵ , we have the relation under a constant stress,

$$d\bar{\sigma}/d\epsilon = 1/F \quad (6)$$

Referring to Eq. (5), the next relation is obtained,

$$(1/F) \cdot f(\bar{\sigma}, \sigma, T) = (\partial \bar{\sigma}/\partial \epsilon)' \cdot f(\bar{\sigma}, \sigma, T) \\ + (\partial \bar{\sigma}/\partial t)' \quad (7)$$

Since $1/F$ in Eq. (6) is determined from the data of constant stress test, the portion of rate of recovery $(\partial \bar{\sigma}/\partial t_i)'$, which depends on t_i , is not included in $1/F$, as an addition to $(\partial \bar{\sigma}/\partial t)'$. Therefore in order to use the value of $1/F$ in the above, it should be modified by the following procedures. That is, $1/F$ obtained from the data of constant stress creep test is first multiplied by strain rate $f(\bar{\sigma}, \sigma, T)$ as in Eq. (7). Secondly $(\partial \bar{\sigma}/\partial t_i)'$ is added to the product, and then the sum is divided again by $f(\bar{\sigma}, \sigma, T)$. Then $1/F$ applicable for computing deformation under stepwise varying stress may be obtained.

3.2 Characteristic functions

As described above, the three sorts of characteristic functions must be known in order to determine $1/F$. These functions have been determined for SC-14-1⁽⁵⁾, but not for SC-15. Therefore the analysis which follows will be made for SC-14-1.

For SC-15, a conventional method is used. Since the behavior of SC-15⁽²⁾ under a constant stress of 20.0 kg/mm² is similar to that of SC-14-1⁽⁴⁾ under a constant stress of 18.0 kg/mm², we assume that the behaviors under a varying stress are also similar to each other, and that the stress ranges of A' (20.0~18.0), B' (20.0~14.0) and C' (20.0~0) for SC-15 correspond to those of A (18.0~16.0), B (18.0~12.0) and C (18.0~0) for SC-14-1, respectively. Then we may qualitatively compare the analysis for SC-14-1 with the experiment for SC-15 in a corresponding stress range, and may quantitatively discuss the relations between analysis and experiment using the ratio $(\epsilon_{vs}/\epsilon_{cs})$ at a given value of $\bar{\epsilon}$.

The characteristic functions used in this study are as follows.

$$f(\bar{\sigma}, \sigma, T):$$

The following experimental expression has been determined for SC-14-1⁽⁵⁾, the general form

of the formula being derived by modifying the Kauzmann's equation,

$$f(\bar{\sigma}, \sigma, T) = \frac{1.42 \times 10^{-5}}{\bar{\sigma} - \sigma} \times \sigma^{5.0} \cdot \exp \left[-\frac{8.53 \times 10^2}{RT} (\bar{\sigma} - \sigma)^2 \right] \dots \dots \dots (8)$$

$(\partial \bar{\sigma} / \partial \epsilon)'$:

For SC-14-1, the following has been derived from the stress-strain curve of tension test conducted at a constant very high rate of strain⁽⁵⁾, at which the effect of recovery could be neglected as compared with that of work hardening,

$$(\partial \bar{\sigma} / \partial \epsilon)' = 3.49 \times 10^4 \cdot \bar{\sigma}^{-3.0} \dots \dots \dots (9)$$

$(\partial \bar{\sigma} / \partial t)''$:

It has been determined for SC-14-1 from the results of tension tests conducted at various constant strain rates⁽⁵⁾,

$$(\partial \bar{\sigma} / \partial t)'' = -\{1 + (10^7 \cdot \dot{\epsilon})^{0.85}\} \times 10^{-6.01-0.004\sigma} \bar{\sigma} \dots \dots (10)$$

$(\partial \bar{\sigma} / \partial t)'$:

The expression of $(\partial \bar{\sigma} / \partial t)'$ after stress reduction has been determined for a 0.12 percent carbon steel⁽⁶⁾, neglecting $(\partial \bar{\sigma} / \partial t)'$ after a stress increase. It is written in the form

$$(\partial \bar{\sigma} / \partial t)' = (\partial \bar{\sigma} / \partial t)_1' \cdot \frac{b'}{1 + c_1 t_i} \dots \dots \dots (11)$$

where b' is a coefficient, and c_1 is a constant. For a 0.12 percent carbon steel, b' and c_1 are⁽⁶⁾

$$\left. \begin{aligned} b' &= 3.70 \times 10^{17} \cdot \log e \cdot \epsilon_c \cdot \sigma_0^{-12.8} \\ c_1 &= 10 \end{aligned} \right\} \dots \dots \dots (12)$$

Here we estimate those for SC-14-1, on the basis of Eq. (12). Since creep behaviors under constant stress for SC-14-1⁽¹⁾ and for a 0.12 percent carbon steel⁽⁹⁾ are quite similar, we assume that c_1 for SC-14-1 is also 10.

As already reported⁽⁶⁾, the most important factor influencing the rate of recovery was the magnitude of strain rate. Therefore if the strain rates at a given time were the same for two similar materials, the characteristics of the rate of recovery would also be quite similar to each other. Then with such materials, we assume that the values of b'/ϵ_c are the same between the two if the

strain rates at a given time are the same. Applying this assumption to SC-14-1 and a 0.12 percent carbon steel, we have

$$b' = 1.13 \times 10^{18} \cdot \log e \cdot \epsilon_c \cdot \sigma_0^{-12.8} \dots \dots \dots (13)$$

for SC-14-1. Then

$$\begin{aligned} (\partial \bar{\sigma} / \partial t)' &= -\{1 + (10^7 \cdot \dot{\epsilon})^{0.85}\} \times 10^{-6.01-0.004\sigma} \\ &\times \frac{1.13 \times 10^{18} \log e}{1 + 10t_i} \cdot \frac{\epsilon_c}{\sigma_0^{12.8}} \dots \dots \dots (14) \end{aligned}$$

$(\partial \bar{\sigma})_0$:

In a previous study⁽²⁾, it was found that the value of $\bar{\sigma}$ just before a stress change was not equal to that immediately after the stress change. The magnitude of the discrepancy $(\partial \bar{\sigma})_0$ has been determined for a material having the same nominal chemical composition as SC-14-1, as⁽²⁾

$$\begin{aligned} (\partial \bar{\sigma})_0 &= \frac{3}{4} \Delta \sigma [1 - \exp \{-1.5(\epsilon_1 - \epsilon_{01})\}] , \\ &= 0 \quad \left. \begin{aligned} &\epsilon_1 - \epsilon_{01} \geq 0 \\ &\epsilon_1 - \epsilon_{01} < 0 \end{aligned} \right\} \dots \dots (15) \end{aligned}$$

Then we may apply this also to SC-14-1.

4. Calculation of creep deformation under periodic stresses of rectangular wave

4.1 Examples [I] using $1/F$ determined from the characteristic functions

$1/F$ is calculated using Eqs. (8), (9), (10) and (14). Deformation can be determined by Eqs. (4) and (5). Fig. 1 shows the calculated results of (IIC-1440-10) and (IIC-1440-1) for SC-14-1, in addition to the calculated result of test under a constant stress of $\sigma_{\max}$. In order to compare these analytical curves with the experimental results, Fig. 2 is presented, where the circles and the full lines indicate the experimental results. As is known from the figures, the two curves under periodic stresses are higher than the creep curve under the constant stress, the magnitude of which is equal to the maximum stress $\sigma_{\max}$ in varying stress tests. It is also said, from comparison of both curves by experiment and calculation, that the deformation is larger for a small value of τ/p .

The calculation by this method is found to agree considerably well with the experiment. However, as recognized from precise comparison of Fig. 1 with Fig. 2, the experimental and the calculated $\epsilon - \bar{t}$ relations, for instance, the creep curves for a constant stress, differ to some extent in quality as well as in quantity. The discrepancy would be caused by inaccuracies in the characteristic functions, which have been determined from the data of constant strain rate tension tests⁽⁵⁾, used in determination of $1/F$.

Fig. 1 Calculated relations of ϵ to $\bar{t}$ using $1/F$ determined from the characteristic functions

4.2 Examples [II] using $1/F$ determined from the results of constant stress creep tests

In this section, some examples of analysis using $1/F$ determined in another way are described.

$1/F$ can also be determined from the data of constant stress creep tests, as described in 3.1. If the value of $1/F$ thus determined were used for calculating the $\epsilon-\bar{t}$ relation, a better coincidence than in the preceding section would be expected between calculation and experiment, since the value of $1/F$ results as if it were checked and corrected by the experiment.

In this section, $1/F$ was determined from the data of constant stress creep tests which have been

previously reported⁽¹⁾, together with Eqs. (8) and (14). In calculation of deformation, Eq. (15) was also used for $(\partial\bar{\sigma})_0$.

4.2.1 Influence of τ/p on deformation

In Fig. 2 the calculated results for both (IIC-1440-10) and (IIC-1440-1) of SC-14-1 are shown by the one-dotted chain lines. In the figure the experimental results are also illustrated by circles and full lines. The broken line in the figure represents a creep curve under a constant stress of $\sigma_{\max}$, which at the same time represents the $\epsilon-\bar{t}$ relation of (IIC-1440-10) or (IIC-1440-1) calculated by the mechanical equation of state. The calculation in this section is in good agreement with the experiment. The smaller τ/p gives the larger strain at given $\bar{t}$.

Fig. 3 shows the calculated relations of ϵ to $\bar{t}$ for (IIB-1440-10), (IIC-1440-10), (IIB-1440-1) and (IIC-1440-1). These agree also considerably well in quality with the experiment of SC-15. As for the relation of (IIIA-1440-10) shown in Fig. 3, we shall refer to it in the next item.

Fig. 4 compares the calculation with the experiment in the form

Fig. 2 Comparisons of the calculation using $1/F$ obtained from the constant stress creep data with the experiment

Fig. 3 Influences of τ/p and stress ranges on deformation

Fig. 5 Influence of τ/p on deformation by changing p at constant $\tau=144$ min

Fig. 4 A quantitative comparisons of the calculation with the experiment

Fig. 6 Comparisons of the calculation with the experiment

of $(\epsilon_{vs}/\epsilon_{cs}) - \bar{t}$ relation. The calculation by the present method, represented by the one-dotted chain line, is also quantitatively in good agreement with the experiment represented by the full line, although it appears that the latter is slightly larger than the former.

In the above, the effect of τ/p on deformation has been examined by changing τ with p kept constant. Next we study it by changing p at constant $\tau=144$ min. Fig. 5 shows the calculated results of (IIC-288-50), (IIC-1440-10) and (IIC-13824-1) for SC-14-1, following the assumption of section 3.2. In these cases also the strain ϵ at a given $\bar{t}$ is larger for smaller τ/p , as was seen in the experiment⁽²⁾. A quantitative comparison between the calculation (illustrated by one-dotted

chain line) and the experiment (illustrated by full line) is made in the relation of $(\epsilon_{vs}/\epsilon_{cs})$ to $\bar{t}$ in Fig. 6. Considering that the values of $(\epsilon_{vs}/\epsilon_{cs})$ until $\tau=144$ min, i.e. during the application of $\sigma_{\max}$ in the first cycle, should be unity for every test, it may be concluded that the coincidence is also good in this case.

4.2.2 Influence of $\sigma_{\min}$ relative to $\sigma_{\max}$ on deformation

In the calculation of this section, $\sigma_{\min}$ appears to affect little the deformations at a given $\bar{t}$ under periodic stresses in the stress ranges of A, B and C, as is seen in Figs. 3 and 4. This may be due to the fact that for larger $(\sigma_{\max} - \sigma_{\min})$ the rate of recovery is mainly controlled by the portion of rate of recovery represented by Eq. (14), which is

Fig. 7 Influence of p on deformation at $\tau/p=1.04\%$

Fig. 8 Influence of p on deformation at $\tau/p=10\%$

Fig. 9 Influence of p on deformation at $\tau/p=50\%$

Fig. 10 $\epsilon - \bar{t}$ relations under periodic stress of type (IV) for (a) the experiment and (b) the calculation

affected by the state values just before the stress change. When $(\sigma_{\max} - \sigma_{\min})$ becomes smaller than 2 kg/mm^2 , however, the effect of $\sigma_{\min}$ on deformation may appear in $\epsilon - \bar{t}$ relation, because the portion of rate of recovery represented by Eq.(10) becomes comparable to that by Eq. (14).

4.2.3 Influence of p on deformation

Figs. 7 and 8 show the calculated relations of ϵ to $\bar{t}$ for two sorts of period, at $\tau/p=1\%$ in a stress range of C and at $\tau/p=10\%$ in a stress range of B, respectively. It is seen from the figures that the strain at a given time $\bar{t}$ is greater for shorter p , as was observed in the experiment⁽²⁾

Fig. 9 illustrates the analytical results at $\tau/p=50\%$ in a stress range of A. In the experiment the influence of period on deformation was not so clear because of scatter of the experimental results⁽¹⁾⁽²⁾. In the calculation, however, the influence of period on deformation is distinctly recognized that the strain at a given time $\bar{t}$ is greater for shorter period p .

4.2.4 Calculation of deformation under a periodic stress of type (IV)

In the above, the deformation under periodic stress of type (III) was discussed. In this item, the deformation under another stress of type (IV) is computed in a similar way. Fig. 10 shows the calculated results of (IVB-11520) in comparison with the experimental results, which were obtained with SC-15 in a stress range of B'⁽²⁾. The calculation illustrated in Fig. 10 (b) shows a very close trend with the experiment in Fig. 10 (a).

5. Conclusion

The creep deformation of mild steel under periodic stresses of rectangular wave was calculated by the authors' theory of plastic deformation of metals at high temperatures. The calculated results were compared with the experimental results which have

been reported in the previous paper⁽²⁾. From the comparison, it was found that the agreement of the calculation with the experiment was considerably good even under such condition of varying stresses that the ratio of time under the stresses higher than the mean stress to that under the stresses lower than the mean stress was quite smaller than unity. Since there is practically no available method to predict deformation without any limitation in stress-time pattern, the authors' theory of deformation would be useful in predicting deformation under varying stresses (and probably also varying temperatures), although further development of the theory in this line should be made.

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