539.376:539.434:539.389.4

Creep of Mild Steel under Periodic Stresses of Rectangular Wave*

(II) Creep Deformation under Unsymmetrical Periodic Stress Waves

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

Creep of mild steel was studied at a temperature of 450°C under unsymmetrical periodic stresses such that in a stress cycle the time under stresses higher than the mean stress was shorter than the time under stresses lower than the mean stress. It was found that in this case the mechanical equation of state in solid predicted a smaller deformation as compared with the one obtained by experiment, while it had been applicable without any appreciable error in the case of a symmetrical stress wave. It was also ascertained that the smaller the ratio of the loading time of the higher stress to that of the lower stress and the shorter the period of a stress cycle, the more the tendency was accentuated, although the lower stress affected little the total deformation under a given stress wave provided that the higher stress was constant.

1. Introduction

The authors have reported in a previous paper⁽¹⁾ the creep of mild steel under the varying stress of symmetrically rectangular wave. In the paper, the creep deformation under symmetrical stress changes with respect to the mean stress was well predicted by the analysis based on the mechanical equation of state in solid⁽²⁾, or often called the strain hardening theory, using the data of the constant stress creep tests. However, it was also foretold from theoretical discussion that a good coincidence of the prediction with the experiment would not usually be obtained, when the experimental conditions such as pattern of stress wave, magnitude of the applied stresses, testing temperatures and so on, were different from those described in the paper. As an example, it was predicted that under an unsymmetrical stress wave, where the time under the stresses higher than the mean stress was much shorter than the time kept at the stresses lower than the mean stress, the creep deformation would be much

larger than the predicted one by use of the mechanical equation of state in solid.

In the present paper, therefore, the influence of the mode of pattern of stress wave on the creep deformation is tested at a temperature of 450°C employing the same material as that used in the previous study⁽¹⁾, with special reference to the case where the time under the higher stresses is shorter than the time under the lower stresses. The results are discussed primarily from the viewpoint of the prediction of creep strain by the mechanical equation of state, and also from the authors' theory of deformation⁽³⁾ in a supplementary manner. The studies in this line are considered as one of the most important branches in engineering researches.

2. Experimental equipments and test specimens

2.1 Fundamental patterns of stress wave

The experimental results for the stress waves (I) and (II) as shown in Fig. 1 have been reported in separate papers⁽¹⁾⁽⁴⁾ by the authors. In the present paper the experiments are mainly conducted under the stress wave of (III) in Fig. 1 and partly under the stress wave of (IV), which is a modified pattern of (II). The symbols in Fig. 1 are as follows.

$\sigma_{\max}$: maximum stress

* Received 3rd February, 1960.

** Professor, Faculty of Engineering, Kyoto University.

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

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

$\sigma_{\min}$: minimum stress
 $\sigma_m = (\sigma_{\max} + \sigma_{\min})/2$: mean stress
 $\sigma_a = (\sigma_{\max} - \sigma_{\min})/2$: stress amplitude
 $\Delta\sigma$: magnitude of step of a stress change
 p : period of stress wave
 t : time after the start of test
 τ : time under the maximum stress in one period

Table 1 Symbols for stress ranges

Symbol	Stress range	
	$\sigma_{\max}$ kg/mm ²	$\sigma_{\min}$ kg/mm ²
A	18.0	16.0
B	18.0	12.0
C	18.0	0.0
A'	20.0	18.0
B'	20.0	14.0
C'	20.0	0.0

Table 2 Chemical compositions of the materials tested

Symbol of material	Chemical composition in percent				
	C	Si	Mn	P	S
SC-14-1	0.14	0.29	0.41	0.010	0.029
SC-15	0.15	0.26	0.43	0.013	0.007

Table 3 Mechanical properties of the materials at room temperature

Symbol of material	Yield point σ_s kg/mm ²	Ultimate strength σ_B kg/mm ²	Elongation ϕ %	Reduction in area ψ %
SC-14-1	24.9	39.1	37.4	72.8
SC-15	23.2	39.4	34.6	68.5

Fig. 1 Stress-time patterns of periodic stresses

$\bar{t}$: total time under the maximum stress in a test

$(\bar{t} = \sum \tau, \text{ when the final period has been finished.})$

In the present study, the influences of the magnitude of τ/p , $\sigma_{\min}$ relative to $\sigma_{\max}$, and p on creep deformation of mild steel are examined for the stress pattern of (III) in Fig. 1. An experiment is also carried out for the stress pattern of (IV) in Fig. 1. For simplicity of description which follows, symbols A, B, C, A', B' and C' are used for various combinations of $\sigma_{\max}$ and $\sigma_{\min}$, as shown in Table 1. As the fundamental units, kg/mm² for stress, min for time and period, and % for strain and τ/p are used.

2.2 Experimental equipments

The experiments under periodic stresses were conducted with the creep testing machine of constant stress type by employing a device for applying or removing stepwise a load⁽¹⁾⁽⁴⁾. This device was regulated to follow a prescribed program by cam mechanism combined with micro-switches. For the experiments, in which the length of period p was longer than 1 440 min (i.e. 1 day), the load was changed manually following a given pattern of stress wave.

2.3 Test specimens

Test specimens were 6 mm in diameter and 50 mm in gauge length⁽⁵⁾. They were made of rolled round bars of two sorts of mild steel of 25 mm in diameter, the chemical compositions of which are shown in Table 2. The material SC-14-1 is the same as the one used in the previous studies⁽¹⁾⁽⁴⁾

All test specimens were annealed at a temperature of 900°C for one hour in vacuum after the finish of machining. The mechanical properties at room temperature after annealing are shown for these two sorts of material in Table 3.

3. Results of experiments

The tests were all conducted under an isothermal condition at 450°C. The creep deformation was represented by logarithmic strain.

For simplicity of description of experimental condition, each test is symbolized as in Table 4, for respective combination of test conditions. For example, the symbol (IIIC-1 440-10) represents the test conducted under a stress wave of pattern (III) in Fig. 1, at a stress range C in Table 1, i.e. 18.0 to 0 kg/mm². The period p of the stress wave is 1 440 min and the magnitude of τ/p is 10 %. In

these symbols, the magnitude of τ/p is written as 1 % for the case of $\tau/p=1.04$ % only for abbreviation of symbol. For stress wave of pattern (IV), the last number in the symbol, which represents the magnitude of τ/p in percent, is omitted, since the magnitude of τ/p for this stress wave is constant, i.e. 12.5 %.

3.1 Results of the constant stress creep tests

In order to obtain reference data to the results of varying stress creep tests, the constant stress creep tests were first conducted.

With the material SC-14-1, the results were reported in another paper⁽¹⁾. The creep curve was represented as

$$\epsilon = \epsilon_0 + \beta t^n + \kappa t \quad \dots\dots\dots (1)$$

where ϵ_0 , β , κ and n are expressed as a function of applied stress σ as

$$\left. \begin{aligned} \epsilon_0 &= 3.13 \times 10^{-6} \cdot \sigma^{4.41} \\ \beta &= 8.34 \times 10^{-4} \cdot \sigma^{1.91} \\ \kappa &= 3.25 \times 10^{-17} \cdot \sigma^{9.44} \\ n &= 2.31 \times 10^{-2} \cdot \sigma - 1.27 \times 10^{-1} \end{aligned} \right\} \dots\dots\dots (2)$$

For the material SC-15, the results are shown in Fig. 2 in the form of strain rate to time relation. For this material, the tertiary creep is seen to appear in rather earlier time than in the case of SC-14-1. However, if we confine the discussion to the phenomena in the primary and secondary creep, the creep curve of SC-15 may also be represented by Eq. (1), and ϵ_0 , β , κ and n can be expressed as

$$\left. \begin{aligned} \epsilon_0 &= 2.09 \times 10^{-1} \cdot \sigma - 3.13 \\ \beta &= 6.25 \times 10^{-1} \\ &\quad - \sqrt{1.06 \times 10^{-1} - 2.93 \times 10^{-3} (20 - \sigma)^2} \\ \kappa &= 1.88 \times 10^{-20} \cdot \sigma^{11.5} \\ n &= 2.57 \times 10^{-2} \cdot \sigma - 3.18 \times 10^{-1} \end{aligned} \right\} \dots\dots\dots (3)$$

The use of expressions of Eq. (3) is limited within the stresses from 14.0 to 22.0 kg/mm². The broken lines in Fig. 2 show the computed results by Eqs. (1) and (3). These curves coincide well with the results of experiments in primary and secondary stages of creep.

3.2 Results of the creep tests under stress wave of type (III)

The tests were conducted under a constant maximum stress of 18.0 kg/mm² for SC-14-1 and 20.0 kg/mm² for SC-15 respectively, by changing the magnitudes of stress range ($\sigma_{\max} - \sigma_{\min}$), period p and ratio τ/p .

Fig. 2 Strain rate-time relations of SC-15 under various constant stresses

Table 4 Symbols for combinations of test conditions

Symbol	Stress time pattern	Stress range kg/mm ²	p min	τ min	τ/p %	Testing duration min	Material
IIIA-5760-50	III	18.0~16.0	5760	2880	50	11520	SC-14-1
IIIA-1440-50		18.0~16.0	1440	720	50	11520	
IIIA-250-50		18.0~16.0	250	125	50	11625	
IIIA-10-50		18.0~16.0	10	5	50	11520	
IIIC-1440-10		18.0~0.0	1440	144	10	47520	
IIIC-1440-1		18.0~0.0	1440	15	1.04	57600	
IIIA'-1440-10		20.0~18.0	1440	144	10	38880	SC-15
IIIB'-1440-10		20.0~14.0	1440	144	10	36000	
IIIB'-1440-1		20.0~14.0	1440	15	1.04	34560	
IIIB'-240-10		20.0~14.0	240	24	10	36240	
IIIC'-1440-10		20.0~0.0	1440	144	10	28800	
IIIC'-1440-1		20.0~0.0	1440	15	1.04	57600	
IIIC'-13824-1		20.0~0.0	13824	144	1.04	69264	
IIIC'-288-50		20.0~0.0	288	144	50	1872	
IVB'-11520	IV	20.0~14.0	11520	1440	12.5	25920	

3.2.1 Influence of stress range on creep deformation

Fig. 3 shows the ϵ - $\bar{t}$ relations of SC-15 for three sorts of stress range A' (20.0~18.0), B' (20.0~14.0) and C' (20.0~0), which are given in Table 1, at $p=1440$ min and $\tau/p=10$ or 1%. It is found that the curves can be classified into either of the two groups of curves corresponding to $\tau/p=10\%$ and 1% respectively. The discrepancies in curves in each group are quite small for wide variation of stress range. Therefore we can say that the value of minimum stress affects little the strain at a given total loading time $\bar{t}$ under maximum

stress, when $\sigma_{\max}$, p and τ/p are kept constant and the magnitude of $(\sigma_{\max}-\sigma_{\min})$ is at least greater than about 2 kg/mm² for maximum stress of about 20 kg/mm². Although the limit of the value of $(\sigma_{\max}-\sigma_{\min})$ for a given $\sigma_{\max}$, which does not affect the ϵ - $\bar{t}$ curves, is not clarified from this experiment, it is supposed that this trend may be observed when the strain under minimum stress is sufficiently small as compared with the strain under maximum stress. The broken lines in Fig. 3 show the computed results by the mechanical equation of state. The computation gives much smaller strain than the experiment.

3.2.2 Effect of τ/p on creep deformation

Fig. 4 shows the ϵ - $\bar{t}$ relations of SC-14-1 for two sorts of τ/p , i.e. 10% and 1%, under a given stress range of C (18.0~0) at a constant period $p=1440$ min. The broken line in the figure illustrates the computed results by the mechanical equation of state. The calculation does not coincide with the experiment, but the latter is much larger than the former. This trend becomes more pronounced for smaller value of τ/p . With the material SC-15, the situation is also quite the same, as seen in Fig. 3.

For the examples shown in Figs. 3 and 4, the value of τ/p was changed by varying the time τ under maximum stress in a period p , keeping p constant. Then the experiments studying the influence of τ/p were also carried out by changing the period p and maintaining τ constant.

Fig. 5 shows the ϵ - $\bar{t}$ relations of SC-15 for $\tau/p=50$, 10 and 1 (more strictly 1.04)% at constant value of $\tau=144$ min, the values of p being 288, 1440 and 13824 min respectively. In this case, the strain ϵ at a given total loading time $\bar{t}$ under maximum stress is also greater for smaller τ/p . In the figure, the strain at $\tau/p=1\%$ appears smaller than that at $\tau/p=10\%$. This may be due to the scatter of the properties of material, which is essentially unavoidable.

Fig. 3 Influence of stress range and ratio τ/p on creep of SC-15

Fig. 4 Influence of ratio τ/p at a constant period $p=1440$ min on creep of SC-14-1

Fig. 5 Influence of ratio τ/p at a constant time $\tau=144$ min on creep of SC-15

Fig. 6 Comparison of strains of SC-15 after $\bar{t}=144$ min for the cases shown in Fig. 5

Fig. 7 Influence of period p on creep of SC-15 at $\tau/p=1.04$ %

able in the testing material. That is, at the end of the time of the first loading of the maximum stress, i.e. $\bar{t}=144$ min, the strain for $\tau/p=1$ % is considerably smaller than that for $\tau/p=10$ %. However, if the relations of $\varepsilon'=(\varepsilon-\varepsilon_{144})$ to $\bar{t}'=(\bar{t}-144)$, instead of those of ε to $\bar{t}$, are compared between the two as shown in Fig. 6, where ε_{144} means strain at $\bar{t}=144$ min, it is found that the strain for $\tau/p=1$ % becomes greater than that for $\tau/p=10$ %.

3.2.3 Effect of period p on creep deformation

For the results under stress waves (I) and (II), the effect of period p on creep strain was negligibly small and could not be distinguished from experimental error and scatter of properties of material⁽¹⁾⁽⁴⁾. From the results described above, however, it is considered to be incorrect to conclude that the influence of period on creep is absent or if any very small in any case, because the results in the previous studies⁽¹⁾⁽⁴⁾ might be due to a high value of τ/p , at which the effect of varying stress is very small and would be buried in scatter band of experimental results. Therefore it is suspected that some different results might be obtained, if the experiments were conducted for sufficiently small value of τ/p .

In this study, the experiments were made for small value of τ/p . Then the results for $\tau/p=50$ %, i.e. the results in the previous study⁽¹⁾, were also

Fig. 8 Influence of period p on creep of SC-15 at $\tau/p=10$ %

examined again on the basis of the finding of this study.

Figs. 7 and 8 show the ε - $\bar{t}$ relations of SC-15 for two values of period p at $\tau/p=1$ % and 10 % respectively. In each figure, strain at a given $\bar{t}$ is greater for shorter length of period p .

For $\tau/p=50$ %, the results reported in the previous paper⁽¹⁾ can be replotted in ε - $\bar{t}$ relations as in Fig. 9. The broken lines in the figure show the calculated results for $p=10$ min and for the constant stress creep tests of 18.0 kg/mm². Although the effect of period on creep deformation is not

clear from the figure owing to the scatter of experimental results, a similar trend described above may be recognized a little, if only the increment due to the application of varying stress is detected.

3.3 Result of the creep test under stress wave of type (IV)

The creep curve of SC-15 under a condition of (IVB'-11520) is shown in Fig. 10. The broken line in the figure illustrates a creep curve calculated by the mechanical equation of state. From the figure it is understood that the majority of deformation takes place during the application of maximum stress, and the contribution of strain increments under the stress levels other than the maximum stress to the total strain is very small. Some discrepancy also exists between the experiment and the calculation in this example.

4. Discussion

4.1 Comparison of experiment with calculation by the mechanical equation of state

The mechanical equation of state in solid, or often called the strain hardening theory, consists in the assumption⁽²⁾ that the strain rate at any instant may be determined uniquely as a function

of the current values of strain, applied stress and temperature. That is

$$d\epsilon/dt = h(\epsilon, \sigma, T) \quad (4)$$

For example, if the data of constant stress creep tests were used as referring data, the fundamental equation of the theory corresponding to Eq. (4) would be reduced by eliminating t from Eq. (1) and its derivative with respect to t ,

$$d\epsilon/dt = n\beta t^{n-1} + \kappa \quad (5)$$

As described, the broken lines in Figs. 3 to 10 inclusive indicate the calculated results for each combination of test conditions. Under the test conditions in this study, the strain by the experiment is larger than the strain by the calculation. This trend becomes more remarkable for larger value of $(\sigma_{\max} - \sigma_{\min})$, for smaller value of τ/p and for shorter length of period p . These coincide qualitatively well with the predictions⁽¹⁾ by the authors' theory, which were made by comparing the authors' theory with the mechanical equation of state.

From the comparison between the experiment and the calculation, it is clear that the most important factor affecting the deformation is τ/p . The discrepancy between the calculation and the experiment becomes gradually pronounced, when

τ/p is made smaller than 50 %.

4.2 Discussion of the results based on the authors' theory of plastic deformation at high temperatures⁽³⁾

In the previous paper⁽¹⁾, the limitation of prediction of deformation by the mechanical equation of state in solid was discussed on the basis of the general theory of plastic deformation at high temperatures proposed by the authors⁽³⁾. The results of the discussion were found to be true at least qualitatively, as mentioned above. In the discussion of the previous paper, the characteristic function such as

$$F(\bar{\sigma}, \sigma, T) = 1/[(\partial \bar{\sigma}/\partial \epsilon)' + (\partial \bar{\sigma}/\partial t)/f(\bar{\sigma}, \sigma, T)] \quad (6)$$

was considered as functions of variables of internal yield stress $\bar{\sigma}$, applied stress σ and temperature T , where $(\partial \bar{\sigma}/\partial \epsilon)'$ represented the work hardening function or the coefficient of work

Fig. 9 Influence of period p on creep of SC-14-1 at $\tau/p = 50\%$

Fig. 10 Creep curve of SC-15 under the stress of type (N)

hardening, $(\partial\bar{\sigma}/\partial t)'$ the rate of recovery and $f(\bar{\sigma}, \sigma, T)$ the strain rate function. In the course of the studies⁽⁶⁾⁽⁷⁾⁽⁸⁾ to determine the actual forms of these characteristic functions, however, it has been found that these functions, especially the rate of recovery $(\partial\bar{\sigma}/\partial t)'$, behaves also as a function of time when a sudden change in stress or strain rate is given. Some other natures regarding these characteristic functions have also been revealed. Therefore in this paper we shall modify and develop the results of discussion developed in the previous paper⁽¹⁾.

If $(\partial\bar{\sigma}/\partial t)'$ is a function of t_l , in addition to $\bar{\sigma}$, σ and T , the function F in Eq. (6) at constant σ and T is no longer an one-variable function of $\bar{\sigma}$. Then the fundamental differential equations,

$$\left. \begin{aligned} d\varepsilon &= F(\bar{\sigma}, \sigma, T; t_l) d\bar{\sigma} & d\varepsilon \geq 0 \\ dt &= \frac{F(\bar{\sigma}, \sigma, T; t_l)}{f(\bar{\sigma}, \sigma, T)} d\bar{\sigma} & d\bar{\sigma} \geq 0 \end{aligned} \right\} \dots\dots\dots (7)$$

are not of variable separable type under constant stress at isothermal condition. It is not correct, therefore, to discuss, for example, the relation of ε to $\bar{\sigma}$ from the relation of F to $\bar{\sigma}$. For mild steel, however, $(\partial\bar{\sigma}/\partial t)'$ is given as a sum of the portion represented as functions of $\bar{\sigma}$, σ and T , and the one represented as functions of $\bar{\sigma}$, σ , T and t_l , where t_l means the time elapsed after the stress change⁽⁷⁾⁽⁸⁾. The effect of t_l on the latter is expressed as $1/(1+c_1 t_l)^{c_2}$. Therefore although change in rate of recovery with time t_l is considerable for some period after the stress change, it becomes slower and may be taken approximately as a constant after a sufficient time has elapsed. In this stage, the rate of recovery is considered only to have increased by a certain amount, and qualitatively the same result as in the previous study⁽¹⁾ may be obtained through a similar discussion as in the previous paper.

Regarding the characteristics of the rate of recovery⁽⁶⁾⁽⁷⁾,

(i) the portion depending on $\bar{\sigma}$, σ and T is written approximately as a function of the current rate of strain, and

(ii) the portion depending on t_l in addition to $\bar{\sigma}$, σ and T is affected also by the magnitudes of $\bar{\sigma}$, strain rate and strain, just before the stress change, but little by those after the stress change.

In general the strain rate immediately after the stress reduction would be very small as compared with the one before the stress reduction. Then the rate of recovery depending on current strain rate may be negligibly small as compared with that depending on the variables just before the stress change, when the stress is changed suddenly. This

may be the reason why the deformation under the stress wave (III) is scarcely affected by $\sigma_{\min}$, when $\sigma_{\max}$, τ/p and p are kept unchanged.

As for the effect of τ/p , it is interpreted that the longer length of time for recovery, which corresponds to the smaller value of τ/p , may cause the larger increment of strain. For the effect of period p on creep deformation, we can easily understand it from the dependence of recovery rate on t_l .

From the discussion, it is understood that the mechanical equation of state or the strain hardening theory becomes more invalid under the stress range $(\sigma_{\max} - \sigma_{\min})$ greater than a certain magnitude, at smaller τ/p for shorter length of period p , or in other words, under conditions where recovery is more pronounced.

5. Conclusion

The creep deformation of mild steel under stress waves unsymmetrical with respect to mean stress was studied under an isothermal condition of 450°C. The effects of minimum stress $\sigma_{\min}$ at a given maximum stress $\sigma_{\max}$, the ratio τ/p of the loading time under maximum stress $\sigma_{\max}$ to period p in one cycle, and the length of period p , on creep deformation were examined. From the experiment and the discussion, the following are concluded:

(1) The creep deformation by the experiment at any value of τ/p smaller than 50 percent was greater than the one by the calculation following the concept of the mechanical equation of state.

(2) This trend was more remarkable for smaller τ/p , when other variables such as $\sigma_{\max}$, $\sigma_{\min}$ and p (or τ) were kept constant. In general, the strain at a given total loading time $\bar{t}$ under maximum stress is greater for smaller τ/p , if the other conditions are the same.

(3) The strain at a given $\bar{t}$ was greater for shorter length of period p , when other conditions were maintained constant.

(4) The minimum stress $\sigma_{\min}$ affected little the creep deformation if the magnitude of stress range $(\sigma_{\max} - \sigma_{\min})$ was greater than a certain value.

(5) Under any stress wave, such that the ratio of loading time under stresses higher than the mean stress to that under stresses lower than the mean stress is sufficiently smaller than unity, the strain by the experiment may be considered to be greater than that by the calculation. In other words, under such conditions the calculation by the mechanical equation of state would give a value of deformation on dangerous side.

Acknowledgement

The authors are indebted to Mr. T. Kamitani for his assistance in the experimental work. The authors are also grateful to the Sumitomo Metal Industry, Ltd. for supplying the material SC-15 used in this study.

References

- (1) S. Taira, K. Tanaka, K. Ohji, and I. Harumoto: *Bulletin of JSME*, Vol. 2, No. 8, (1959), p. 514.
- (2) C. Zener and J.H. Hollomon: *J. Appl. Phys.*, Vol. 17, (1946), p. 69.
- (3) T. Nishihara, S. Taira, K. Tanaka, and K. Ohji: *Proc. 7th Japan Nat. Congr. Appl. Mech.*, 1957, (1958), p. 31.
- (4) T. Nishihara, S. Taira, K. Tanaka, and K. Ohji: *J. Japan Soc. Test. Mat.*, Vol. 7, No. 56, (1958), p. 254. (in Japanese).
- (5) For example, T. Nishihara, S. Taira, K. Tanaka, and K. Ohji: *Bulletin of JSME*, Vol. 2, No. 5, (1959), p. 102.
- (6) S. Taira, K. Tanaka, and K. Ohji: *Bulletin of JSME*, Vol. 3, No. 10, (1960), p. 228.
- (7) S. Taira, K. Tanaka, and K. Ohji: *Proc. 8th Japan Nat. Congr. Appl. Mech.*, 1958. (1959), p. 255.
- (8) S. Taira, K. Tanaka, and K. Ohji: This Bulletin, p. 254.

539. 376:539. 434:539. 389. 4

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.

* Received 3rd February, 1960.

** Professor, Faculty of Engineering, Kyoto University.

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

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