Creep and Recovery under Cyclic Plastic Strain

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INTRODUCTION

A progressive permanent deformation is observed in materials which are subjected to a cyclic plastic strain superposed with a steady stress, even if the steady stress is much smaller than yield stresses of the materials. In other words, a creep-like deformation is produced by an elastic stress when superposed with plastic strain cycling. This phenomenon is called mechanical ratchetting. The purpose of the present work is to investigate the fundamental feature of the phenomenon by means of an experiment with loading of a cyclic axial strain combined with a steady torsional stress.

EXPERIMENT

The test materials are the following four kinds of commercial steels, (1) 0.45 carbon steel, JIS S45C, (2) low alloy steel, ASTM A302 Grade B, (3) Cr-Mo steel, JIS SCM3, (4) austenitic stainless steel, AISI 304. The test specimen is of a hollow cylindrical shape of 13 mm in O.D., 1.5 mm in wall thickness and 40 mm in G.L.. A hydraulic servo-controlled push-pull low-cycle fatigue tester is used with attachments of a special loading device of a steady torsional stress and a device for accurate measurement of incremental torsional strains during the axial strain cycling. Strain-controlled push-pull low-cycle fatigue tests were conducted with completely reversed triangular strain-time programs for the axial strain on which a steady torsional stress was superposed parametrically.

RESULTS OF THE EXPERIMENT

Observation of the incremental torsional deformation which is produced in each axial strain cycle shows that the deformation fluctuates within a cycle and the fluctuation varies as the cycle progresses. The total residual amount of torsional shear strains at the end of any number of axial strain cycle is denoted by accumulated shear strain, and the increment of torsional shear strain in each strain reversal is denoted by accumulation rate of the shear strain per cycle.

Fig.1 shows the feature of accumulation of the shear strains, where three stages quite similar to those in creep curves are observed. That is, the first stage is a transient one, where the accumulation rate of shear strain decreases gradually. In the second stage, the accumulated shear strain increases almost linearly, so that the accumulation rate is nearly constant. In the third stage, the accumulated shear strain increases rather rapidly, and proceeds to the final fracture.

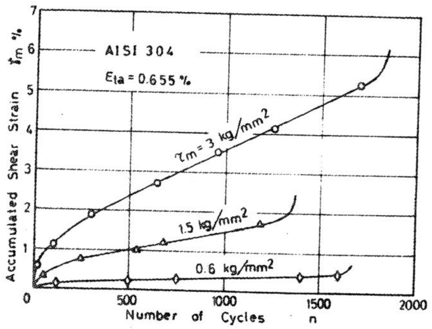

Fig.1 Behavior of Accumulation of Shear Strain

By the analysis of the observed progressive deformations, it is found that there exists a

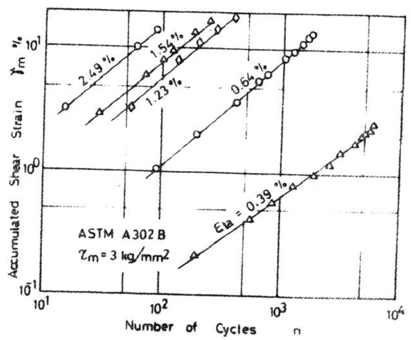

Fig.2 Accumulation Behavior of Shear Strain

fairly good linear relationship between the accumulated shear strain γ_m and the number of axial strain reversal n on a log-log scale. Fig.2 shows an example of the relationship. It is found also that the lineality holds good independent of the magnitude of steady shear stress and the amplitude of cyclic axial strain.

Hence, the following expression is obtained between γ_m and n,

$$\gamma_m = F(\tau_m, \varepsilon_{ta})\, n^k \qquad (1)$$

where τ_m means the steady shear stress and ε_{ta} denotes the amplitude of total (elastic plus plastic) axial strain, and k is a material constant. Further examinations result in the following form of the function $F(\tau_m, \varepsilon_{ta})$ as follows,

$$F(\tau_m, \varepsilon_{ta}) = C(\tau_m - \tau_m^*)(\varepsilon_{ta} - \varepsilon_{ta}^*)^{\alpha} \qquad (2)$$

where τ_m^* and ε_{ta}^* mean the thresholds of the shear stress and the axial strain amplitude respectively for the accumulation of shear strain. And C and α are material constants.

When the steady shear stress is removed or reduced on the way of progress of the axial strain cycle, recovery of the accumulated shear strain is found to occur. Fig.3 shows examples of the feature of recovery of the accumulated shear strain, where the shear stress is completely removed. When the steady shear stress is decreased or increased to another values on the way of progress of the cycle, the accumulation rate of the shear strain varies according to the magnitude of the change of the steady shear stress as shown in Fig.4. From examinations of many experimental data on such variation of the accumulation rate due to the change of steady shear stress, it is found that the

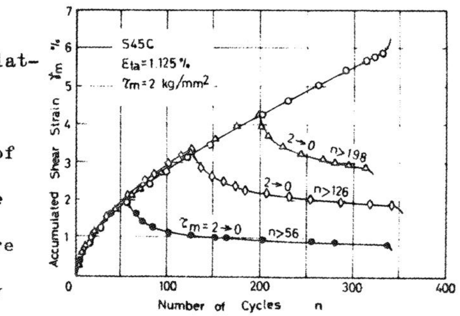

Fig.3 Recovery of Accumulated Shear Strain

magnitude of variation of the accumulation rate of shear strain depends on the difference of magnitudes of the steady shear stresses before and after the change, the amplitude of axial strain and the number of strain reversal at which the steady shear stress is changed.

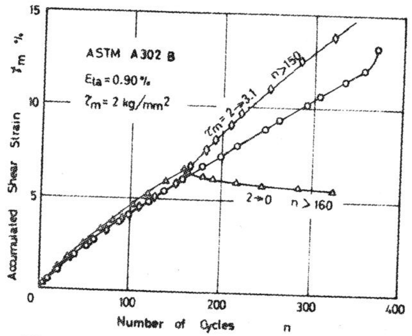

Fig.4 Variation of Accumulation Rate

DISCUSSIONS

From the analysis of the experimental data, it is found that the accumulation rate of shear strain in the second stage of the progress is proportional to the magnitude of steady shear stress and a certain power of the amplitude of axial cyclic stress or strain. It is also shown that the plastic work done by the axial stress and strain in a cycle is the best measure of the loading. Thus, the following general form of the expression is obtained between the plastic work W_p and the accumulation rate of shear strain $\Delta\gamma_m$,

$$\Delta\gamma_m = C(\tau_m - \tau_m^*)(W_p - W_p^*)^{\delta} \qquad (3)$$

where, C and δ are considered to be material constants dependent on temperature. And W_p^* means the threshold value of the plastic work for the accumulation of the shear strain. Fig.5 shows examples of the experimental relation between $\Delta\gamma_m$ and W_p.

As for the behavior of recovery of the accumulated shear strain, it is very likely to hold the following rule of superposition, especially for ferritic steels

$$\Delta\gamma_m = f(\varepsilon_{pr})\sum_i \Delta\tau_{mi}\, g(n-n_i) \qquad (4)$$

where $\Delta\tau_{mi}$ denotes the difference of the steady shear stresses before and after the change, n means the number of strain reversal at any

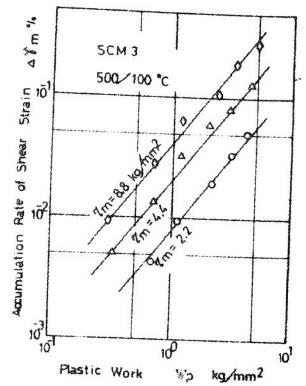

Fig.5 Relation of Accumulation Rate to Plastic Work

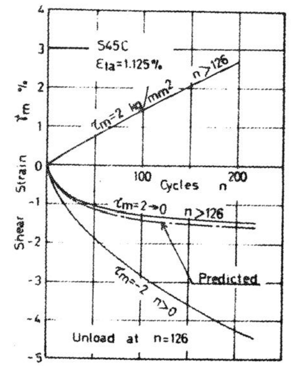

Fig.6 Prediction of Recovery Behavior

moment and n_i means that experienced prior to the change. $f(\varepsilon_{pr})$ means a function of plastic strain range ε_{pr} which has a close relation to $F(\tau_m, \varepsilon_{ta})$ in eq.(2), and $g(n-n_i)$ is $k(n-n_i)^{k-1}$ as is derived from eq.(1). Fig.6 shows a comparison of the recovery curve predicted by eq.(4) and the experimental one.

CONCLUSION

Experimental investigations were made on the progressive deformation under the cyclic plastic strain combined with the steady shear stress. Progress of the shear strain was observed which showed very similar behaviors to those in the creep phenomenon under constant loading. Expressions for the behavior of the progress of the accumulated shear strain were obtained experimentally.

The recovery of the accumulated shear strain was observed in the experiment when the steady shear stress was varied stepwisely. Recovery strain was shown to be predicted with the principle of superposition. It was concluded that the progress of the permanent deformation under cyclic plastic straining showed rather viscous behavior.