Cumulative Damage and Behavior of Plastic Strain below Fatigue Limit

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INTRODUCTION

It is well known that the stress amplitudes below the fatigue limit can do some damage to the materials under the programmed fatigue tests or in service loadings. But at present, the proper estimation for it has not yet been established. The authors have found that the linear cumulative fatigue damage law in terms of the plastic strain range-pair gave good estimations of the fatigue lives in low and high cycle fatigue nearly up to the fatigue limit with the low or medium carbon steels(1).

From such a view point, the programmed fatigue tests having the stress amplitude below the fatigue limit with intermittent high level stress were carried out and the behavior of the plastic strain was investigated.

TEST SPECIMEN AND EXPERIMENTAL PROCEDURE

The material used is a normalized 0.38% carbon steel (880°C×1.2hr, cooled in air) and its chemical composition and mechanical properties are listed in Tables I and II. Test specimens, the dimension of which is shown in Fig.1, were lathed from a bar of 28mm diameter and were polished carefully longitudinally with an emery paper of 0/4.

Repeated two-step programmed fatigue tests were conducted using the push-pull type electro-magnetic fatigue testing machine(2) and the frequency of stress cycling was selected to be 40Hz. The pattern of test loading is shown in Fig.2. The plastic strain was detected by subtracting the elastic strain from the total strain measured by the capacitance bridge type extensometer[2]. This extensometer is designed to have good linearity and it is found that even 0.001% plastic strain can be measured with sufficient accuracy in this investigation.

EXPERIMENTAL RESULTS AND DISCUSSION

The S-N curve of the constant stress amplitude test is shown in Fig.3 and the variation of the plastic strain range during the test in Fig.4. The fatigue limit is 24 kg/mm² and at this stress level 0.06% plastic strain is found to be repeated. And it is observed that there exists the plastic strain at the stress level below the fatigue limit, for example the plastic strain of 0.03% and 0.01% at the stress level of 21 kg/mm² and 19.4 kg/mm², respectively. Therefore, it may be concluded that there is the fatigue limit to the plastic strain as there is to the stress amplitude.

Fig.5 shows an example of the behavior of the plastic strain range-pair $\Delta_{rp}\varepsilon_{p1}$ and $\Delta_{rp}\varepsilon_{p2}$, corresponding to the stress σ_1 and σ_2, respectively, during the repeated two-step programmed test. Values of the plastic strain range-pair increase rapidly with the number of block cycles and reach their saturated values at the early stage of the fatigue life. Affected by the intermittent high level stress σ_1, the saturated value of the plastic strain range-pair $\Delta_{rp}\varepsilon_{p2s}$ corresponding to the stress below the fatigue limit is increased in comparison with that of the constant stress amplitude, although the saturated value $\Delta_{rp}\varepsilon_{p2s}$ is not varied with the level of the stress σ_1 when σ_1 is high enough. On the other hand, the saturated value $\Delta_{rp}\varepsilon_{p1s}$ to the high level stress σ_1 is not affected by the low level stress σ_2. However, when both levels of the stress σ_1 and σ_2 are near to the fatigue limit or the ratio of n_1 to n_2 is very small, the results are

found to be different probably due to the coaxing, and there occurs the case that the specimen does not fail. Fig.6 shows the relation between the half of the stress range-pair and the equivalent plastic strain range-pair $\Delta_{rp}\tilde{\varepsilon}_p$ which is defined by the following equation.

$$\Delta_{rp}\tilde{\varepsilon}_p = \frac{1}{N}\left\{ \sum_{i=1}^{N} (\Delta_{rp}\varepsilon_{pi})^a \right\} \frac{1}{a} \qquad (1)$$

Where a is the reciprocal of the exponent α in the Manson-Coffin formula and nearly equals 2. The relations of the programmed tests are found to be slightly affected by the ratio of n_1 to n_2 and also found to curve downward at the low stress level.

The linear cumulative fatigue damage law in terms of the plastic strain range-pair may be expressed as follows[1][2];

In the constant stress amplitude test,

$$(\Delta_{rp}\tilde{\varepsilon}_p / \varepsilon_0)^a \cdot N = 1 \qquad (2)$$

where N is the number of cycles to failure and ε_0 is a material constant approximately proportional to the fracture ductility ε_f.

In the programmed two-step fatigue test, this damage law is written as follows;

$$(\Delta_{rp}\tilde{\varepsilon}_{p1} / \varepsilon_0)^a \cdot n_1 + (\Delta_{rp}\tilde{\varepsilon}_{p2} / \varepsilon_0)^a \cdot n_2 = 1 \qquad (3)$$

where $\Delta_{rp}\tilde{\varepsilon}_{p1}$ and $\Delta_{rp}\tilde{\varepsilon}_{p2}$ are the equivalent plastic strain range-pair corresponding to the stress σ_1 and σ_2 overall the fatigue life, respectively, and n_1 and n_2 are numbers of cycles of σ_1 and σ_2 to failure, respectively. Since the number of cycles to failure N_1 to $\Delta_{rp}\tilde{\varepsilon}_{p1}$ is known from the constant stress amplitude test results, the imaginary fatigue life N_2 to $\Delta_{rp}\tilde{\varepsilon}_{p2}$ can be estimated. That is,

$$N_2 = n_2 / (1 - n_1 / N_1). \qquad (4)$$

Fig.7 shows the relation between $\Delta_{rp}\tilde{\varepsilon}_{p2}$ and the estimated life N_2. This relation can be expressed as a straight line, independent of the stress level of σ_1 and σ_2, and also the ratio of n_1 to n_2, down to the region below the fatigue limit as shown by BDF and locates approximately on the extended line of AB which is the relation between the plastic strain range and fatigue life in low cycle fatigue. From this results it can be concluded that the fatigue limit in terms of the plastic strain disappears in programmed tests having the intermittent high peak stress and that the fatigue damage caused by the plastic strain range below the fatigue limit is linearly accumulated.

Using the relations shown by Figs.6 and 7, the modified S-N curve in programmed tests can be obtained as shown by BDF in Fig.8. This relation is found to lie below the straight line of the constant stress amplitude test and also found to curve downward at the lower stress level. Therefore, it is concluded that the estimation of fatigue damage caused by the stress below the fatigue limit based on the modified Miner's law or Corten-Dolan type modifications of the S-N curve is under-estimation of damage in the programmed fatigue tests.

REFERENCES

(1) M. Kikukawa and M. Jono, Abstracts of I.C.M.,Kyoto,1,315(1971)

(2) M. Kikukawa, K. Ohji and M. Jono, Proc. Symp. on fatigue of Metals under Service Loads, Japan Society of Mat. Sci.,61(1967)

Table I. Chemical composition of material investigated (%).

Material	C	Mn	Si	P	S	Cu	Ni	Cr
S35C	0.38	0.72	0.25	0.010	0.015	0.04	0.02	0.13

Table II. Mechanical properties of material investigated.

Material	Yield point (kg/mm²)	Tensile strength (kg/mm²)	Elongation (%)	Reduction of area ϕ (%)	Fracture ductility* ϵ_f (%)
S35C	38.0	62.4	23.7	58.5	88.0

* $\epsilon_f = \ln\left(\frac{1}{1-\phi}\right)$

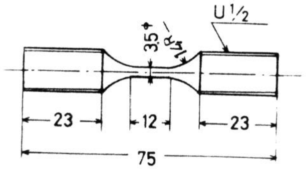

Fig.1 Test specimen

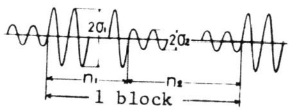

Fig.2 Pattern of test loading

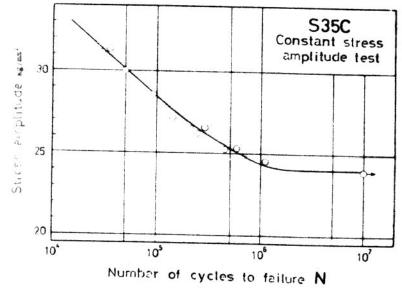

Fig.3 S-N diagram

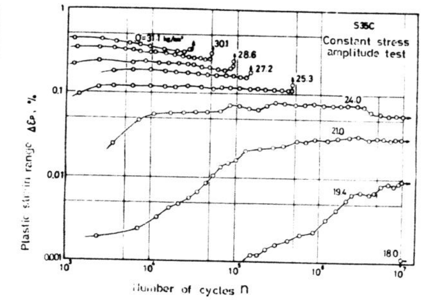

Fig.4 Variation of plastic strain range during constant stress amplitude test

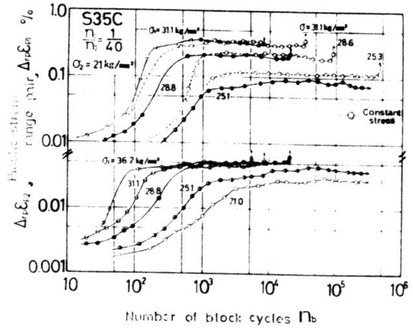

Fig.5 Variation of plastic strain range-pair during repeated two-step fatigue test

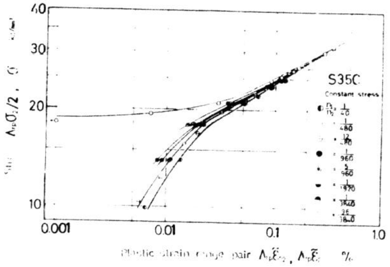

Fig.6 Relation between stress range-pair and plastic strain range-pair

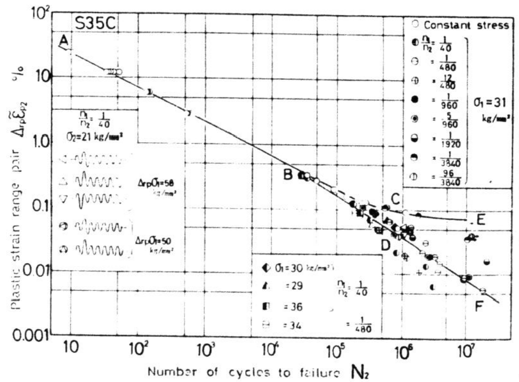

Fig.7 $\Delta_{rp}\tilde{\varepsilon}_{p2} - N_2$ diagram

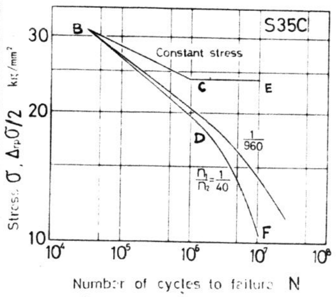

Fig.8 Modification of S-N curve