HIGH-CYCLE AND LOW-CYCLE FATIGUE INTERACTION UNDER 2-STEP STRAIN CONTROL

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Fatigue of mild steel under 2-step strain control of decreasing order with various mean strains has been studied for two different loading sequences. It was observed that cyclic softening in the second step is stabilised by the presence of the first step and either positive or negative mean stress may be induced in the second step. The average damage summations, both with and without mean strain correction, are found to be close to unity. Fatigue damage accumulation has also been analysed using Continuum Damage Mechanics modelling, which helps identify the sources of the deviation of the damage summation from unity and the non-linear accumulation of damage.

INTRODUCTION

Step loading is often taken as an approximation of random loading in fatigue studies due to its controllability. Topper et al(1) found that for fully reversed strain cycling, significant deviation of damage values from unity were observed only when a mean stress was present and the effect of the number of loading blocks is negligible. Bernard-Connolly et al(2) concluded that damage summations were above/below unity for steps in increasing/decreasing order. The damage sums tended to approach unity with the increase of the number of steps. When the difference between the two steps are large enough, an interaction between low and high-cycle fatigue arises as described by Manson(3)(4). Micro-cracking due to plastic strain accumulation and the subsequent damage evolution leading to crack initiation are considered as two major stages of material rapture(5). It is possible to identify the non-linearity of damage accumulation under the framework of Continuum Damage Mechanics(CDM). The aim of this study is to investigate the combined effect of the step amplitude and mean strain/stress on cumulative damage sums proposed by Miner(6) based on the authors' previous work(7). The damage evolution process is also studied by CDM modelling.

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EXPERIMENT

Test Program

The material used was a type AS1214 mild steel whose chemical composition and mechanical properties are given in Ref(7). Two step sequences of decreasing order were chosen. The strain amplitude for step 1 was 0.3% or 0.4% followed by 0.2% for step 2. An interaction between low- and high-cycle is expected. A mean strain of 0.2% was then applied to step 1 and/or step 2 to establish various combinations of strain amplitude and mean strain. The number of cycles applied in step 1 was so determined that approximately 20% of the total fatigue life was consumed(with mean strain corrected) before step 2 was applied.

Test Results and Discussion

Cyclic Stress Amplitude. Fig. 1 shows typical cyclic softening trends. No obvious difference has been observed in cyclic softening with regard to the relative amplitude of the steps and the combinations of the strain amplitude and mean strain. Significant softening occurs in the first step leaving the second step with a considerably lower softening rate compared with the single level test, which can be seen from Fig. 2. It is noted that the stress level in the second step is below that for a single level loading. It was reported that in all decreasing order tests the stress levels in the second and subsequent steps were above or equal to the corresponding stabilised value obtained in standard fatigue tests for a type 304 stainless steel(2).

Mean Stress. Both tensile and compressive mean stresses may be induced in the second step depending on the mean strain combination in the first and the second step. Generally, mean strain in a decreasing order causes negative mean stress, otherwise positive mean stress occurs. Mean stress relaxation curves are shown in Fig. 3. Once again, general trends are the same in mean stress relaxation regardless of the amplitude and mean value combinations of the two steps. Differences, however, do exist in some cases compared with the single level loading.

A continuous mean stress relaxation may exist for the two steps if the mean strains applied for both the first and the second step are the same. Otherwise the trend of relaxation may vary due to a difference in the mean stresses caused by the sudden change of the mean strains.

Cumulative Fatigue Damage. Miner's damage sum $\Sigma n_i/N_{fi}$ was calculated, where n_i is the number of cycles applied at strain amplitude level i and N_{fi} is the fatigue life at the same strain level, which are given in Ref(7). In this study, N_{fi} for both zero mean strain and a specific mean strain are used whenever a mean strain is present to evaluate the effect of mean strain correction on Miner's damage sum. As an example, only damage sums for strain amplitude combination of 0.4%-> 0.2% are plotted in Fig. 4 due to limited space.

The damage sums are more close to unity when the strain amplitude for the first step is larger. This may be attributed to the interaction between high-cycle and low-cycle fatigue due to plastic strain amplitude in the first step. Mean strain correction makes the damage sums deviate from unity and have a larger variance. If mean strain correction is preferred to one of the two steps, the application to the first step results in a damage sum closer to unity and a smaller variance as well.

With mean strain correction, the results indicate a detrimental role of an increasing mean strain and a beneficial effect of a mean strain sequence in a decreasing order. This is consistent with the results reported by Topper and his co-workers(1) in that a tensile mean stress causes an average damage value much smaller than unity whilst a compressive mean stress makes it larger than unity.

A positive mean strain in the first step has demonstrated a beneficial effect on the damage sum without mean strain correction in most of the cases. This was independent of the mean strain value in the second step. However, a negative mean strain in the first step resulted in a damage sum smaller or close to unity.

It has been shown(2)(8) that for the simple cases of a fully reversed step loading, fatigue damage sums are greater/smaller than unity for a loading sequence in an increasing/decreasing order. However, no such a trend is evident with the presence of various mean strains and subsequent mean stresses, which is also supported by the data collected for a SAE 4340 steel by Topper and Sandor(9). The underlying reason may be due to the role of beneficial mean strain/stress in cancelling out the detrimental effect of the preceding high level in initiating cracks.

DAMAGE EVOLUTION PROCESS

According to Continuum Damage Mechanics, the damage rate is proportional to the strain energy density release rate and to the accumulated plastic strain rate beyond a plastic strain threshold and up to a critical value of the damage variable(5). The damage criterion is expressed as $p = p_D$ at microscale and is defined as $D = D_c$ at mesoscale, where p, p_D, D and D_c are accumulated plastic strain, damage threshold for accumulated plastic strain, damage variable and critical damage at crack initiation, respectively. When dealing with fatigue problems, the kinetic law of the damage evolution is directly applicable at mesoscale where significant plastic strain occurs for low-cycle fatigue whilst for high-cycle fatigue the equation must be applied at microscale as plastic strain, if any, is highly localised in micro-inclusion embedded in an elastic mesoelement.

For high-cycle fatigue, assuming an elastic-perfectly plastic material model, it can be shown that:

$$D = D_{1c}\left(N - N_0\right) / \left(N_R - N_0\right) \quad \text{...(1)}$$

where D_{1c} is D_c in tension. Note that damage is proportional to the ratio of $(N - N_0)$ and $(N_R - N_0)$, rather than the ratio of N and N_R. In light of this, for a 2-step loading sequence with n_1 as the number of cycles for step 1 and n_2 as the number of cycles for step 2, damage by n_1 and n_2 is(no sequence effect assumed):

$$D_{(ni)} = D_{1c}\left(n_i - N_{0i}\right) / \left(N_{Ri} - N_{0i}\right) \quad i=1,2 \text{ ....(2)}$$

Applying the failure criterion yields:

$$n_1 / N_{1R} + \left(n_2 / N_{2R} - N_{02} / N_{R2}\right)\left(1 - N_{01} / N_{R1}\right) / \left(1 - N_{02} / N_{R2}\right) = 1 \text{ ....(3)}$$

Thus, $n_1 / N_{R1} + n_2 / N_{R2} = 1$ is valid only when $N_{10} = N_{20} = 0$. Good approximation may be obtained when the amplitudes of the two steps have no big difference where $N_{01} \cong N_{02}$, $N_{R1} \cong N_{R2}$, and n_{02} / N_{R2} is small.

If the effect of the first step on the second step is taken into account, then damage by n_2 can be expressed as follows:

$$D_{(n2)} = D_{1c}\left(n_2 / N_{R2}\right) \quad \text{...(4)}$$

Failure occurs when:

$$\left(n_1 - N_{01}\right) / \left(N_{R1} - N_{01}\right) + \left(n_2 / N_{R2}\right) = 1 \text{ ....(5)}$$

In this case, $n_1 / N_{R1} + n_2 / N_{R2} = 1$ when $N_{10} = 0$ or $n_1 = N_{R1}, n_2 = 0$. The latter one is obviously the case of a constant amplitude loading. When N_{01} is relatively small comparing with N_{R1} and n_1, it is expected that there will be no significant deviation of Miner's damage summation from unity. Experimental results in this study support this argument.

CONCLUSIONS

Fatigue tests of 2-step strain cycling with various combinations of strain amplitude and mean strain have been performed. Results in relation to cyclic deformation in the second step and fatigue damage summation can be summarised as follows.

1. Cyclic softening occurs mostly in the first step where a higher magnitude of strain is applied regardless of mean strains.
2. Both negative and positive mean stresses may be induced in the second step.
3. The damage sum for a strain amplitude sequence of 0.4% -> 0.2% is more close to unity. The damage sums for cases without mean strain correction are closer to unity than those with mean strain correction.
4. A favourable effect has been observed in most cases of positive mean strain applied to the first step on damage sum without mean strain correction; an opposite effect exists for negative mean strain in the first step.
5. With the presence of a mean strain/stress, Hi-Lo sequence does not necessarily cause a damage sum smaller than unity as in the cases with no mean strain/stress.
6 Fatigue damage evolution is analysed by Continuum Damage Mechanics modelling using an elastic-perfectly plastic material model.

REFERENCES

(1) Topper, T. H., Sandor, B. I., and Morrow, JoDean, J. of Materials, Vol. 4, No.1, 1969, pp. 189-199.

(2) Bernard-Connolly, M., Bui-Quoc, T., and Biron, A., J. of Engineering Materials and Technology, Trans. of the ASME, Vol. 105, No. 3, 1983, pp. 188-194.

(3) Manson, S. S., and Halford, G. R., Israel J. of Technology, Vol. 21, 1983, pp. 29-53 (Proc. XXV ISR. Annu. Conf. Aviation and Astronautics 1983).

(4) Manson, S. S., and Halford, G. R., Engineering Fracture Mechanics, Vol. 25, No. 5/6, 1986, pp. 539-571.

(5) Lemaitre, J, A Course On Damage Mechanics, Springer-Verlag, 1992.

(6) Miner, M. S., J. of Applied Mechanics, Trans. of ASME, Vol. 67, 1945, pp A149 -164.

(7) Gong, Y., and Norton, M. P., "Fatigue of Mild Steel with Non-zero Mean Loadings", pp. 145-150, 1996, Proceedings of the First Australasian Congress on Applied Mechanics, Edited by R.H. Grzebieta et al, The Institution of Engineers, Australia.

(8) Dowling, N. E., J. of Materials, Vol. 7, No. 1 , 1972, pp.71-87.

(9) Topper, T. H., and Sandor, B. I., "Effects of Mean Stress and Prestrain on Fatigue-Damage Summation", ASTM STP 462, pp 93-104, 1970, Effects of Environment and Complex Load History on Fatigue Life.

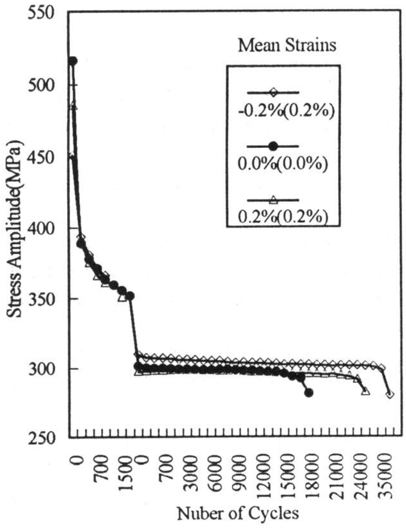

Fig. 1 Cyclic stress amplitude
(strain amplitude 0.3% -> 0.2%)

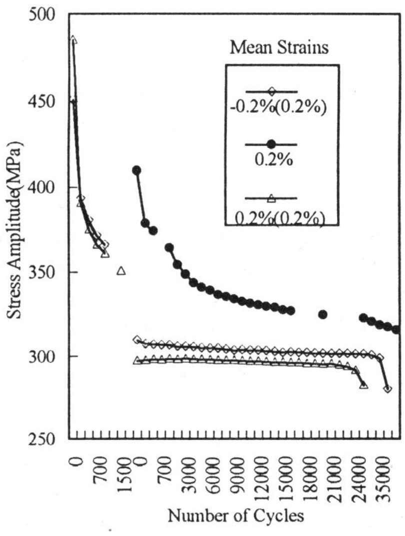

Fig. 2 Comparison of cyclic softening
(strain amplitude 0.3% -> 0.2%)

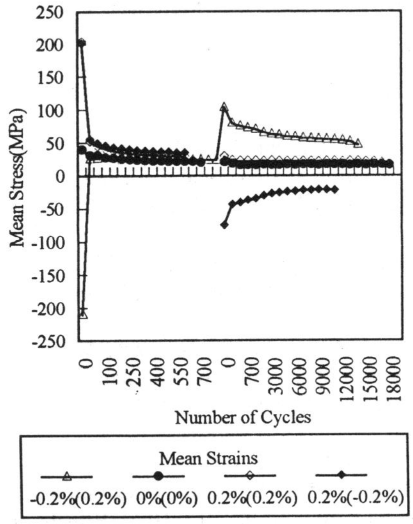

Fig. 3 Mean stress relaxation
(strain amplitude 0.4% -> 0.2%)

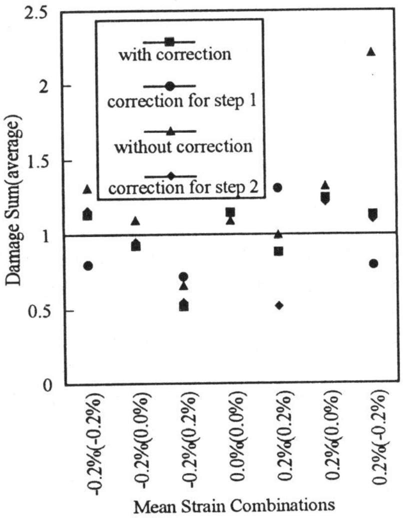

Fig. 4 Comparison of damage sums
(strain amplitude 0.4%->0.2%)