# DI-7 Statistical Aspects of Hardness Distribution of Mild Steel under Repeated Loading

Sakae TANAKA[1] and Shigemi SASAKI[2]

## ABSTRACT

Statistical considerations of the scatter of micro-hardness are presented for mild steel specimen subjected to repeated loading. Influences of cycle number on the variation of mean value and standard deviation of hardness distribution are measured. And the reason why these values fluctuate with repeated cycles, especially in the late stage of fatigue life is discussed experimentally.

## INTRODUCTION

Influence of number of repeated loading on the variation of hardness has been previously measured by several research workers on various materials, and also Mozberg (1) has recentry carried out a detail study on the variation of micro-hardness with repeated cycles for mild steel specimens.

Experiments reported in this paper were undertaken to study statistically the scatter of micro-hardness in connection with the tendency of hardnening and softening of grains during the fatigue process.

In the fatigue tests for annealed mild steel specimens with a rotating bending machine, the distributions of micro-hardness at several numbers of repeated cycles are measured with Micro-Vickers Tester. A diamond-shaped indentation is such a small area as the unit of the grain size as shown in the photograph of Fig.12. On the

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1, 2, Department of Mechanical Engineering, University of Electro-communications, Chōfu-shi, Tokyo, Japan.

hardness distribution which shows approximately normal distribution, variations of the mean value and standard deviation with the number of cycles are observed.

And an examination is attempted to make clear the reason why micro-hardness fluctuates with repeated cycles in the late stage of fatigue life.

## EXPERIMENTAL PROCEDURE

### a) Test specimen

Materials used in the experiment are two kinds of mild steel, one 0.07% and the other 0.24%, and their chemical compositions are shown in Table 1. Specimens were machined to the dimensions shown in Fig.1 from cold drawn circular rod stock with 19 mm diameter. Then surface finish was completed with fine emery paper, and after that, standard heat treatment as shown in Table 2 was given.

Besides, since the ageing effect of Killed steel is very little, for the purpose of comparison with the hardness distributions of the said two kinds of steel, Killed steel specimens were also used in experiments.

### b) Hardness measurement

Fatigue tests were conducted in room temperature and air with a rotating bending machine with the number of revolution 3,000 rpm. Hardness measurements were carried out with Micro-Vickers Tester. At several numbers of repeated cycles during fatigue test, specimen was taken off the testing machine and was measured at 40 points and with the load of 200 gr at the intervals of 0.5 mm in axial direction. This measurement was repeated from 12. to 15 times from the beginning of fatigue test to its fracture on each specimen.

## EXPERIMENTAL RESULTS

S-N relation of testpiece 0.24%-C is shown by white circles in Fig.2. In case of the aforesaid hardness measurement, it is shown by black dots, in which it seems fatigue life of the specimens shows a little increase.

The distribution of the measurement values of hardness at 40 points obtained at each step in fatigue test are arranged as follows. First, they are arranged from smaller values of hardness one by one so that frequencies $f_i$ for intervals of hardness number 2 are obtained, and then their relative cumulative frequencies are plotted on the normal probability paper, which is shown in Fig.3 (a), (b). (a) is the case of 0.07%-C and (b) 0.24%-C. In both of them typical values measured before the test (n = 0), after the fracture (n = N) and twice in the course of those are shown. As these results can be regarded as linear relation in the main, distribution of hardness may well be considered as normal distribution regardless of stress value and number of cycles.

And it will be inferred from these results that mean values and standard deviations of hardness distribution are influenced by the number of cycles. Then arranging all these measurement values, their changed conditions are shown in Fig. 4 and Fig. 5. In both figures, values of hardness and standard deviations are shown against the number of repeated cycles, and in the hardness diagram white circles show the mean values and the upper and lower edges of the vertical lines show the values corresponding to the relative cumulative frequencies of 95% and 5%. The illustration below shows the standard deviations against them.

Also, Fig.6 and Fig.7 are ones that show those distribution characteristics in coefficient of variation. But it should be added that coefficient of variation is taken on the ordinate and cycle ratio on the abscissa.

The following conclusions will be derived from the above experimental results.

1. The distribution of micro hardness in fatigue process shows approximately normal distribution regardless of stress amplitude and number of cycles.
2. The mean value of distribution increases gradually and monotonically with the number of cycles, while after about 10% of fatigue life it comes to take almost a cirtain value and fluctuations increase with it.
3. Standard deviation keeps almost a certain value in the early stage of fatigue process, but its increase and fluctuations are observed after about 10% of fatigue life. This tendency of variation can be more clearly observed when it is shown in coefficient of variation.
4. When the width of hardness distribution is shown by 5% and 95% of relative cumulative frequency, the 5% value does not change too much against the number of cycles, while 95% value does remarksbly, which largely agrees with the tendency of variation of mean value.

## ON THE CAUSE OF THE VARIATION OF HARDNESS

The following examination was attempted to make clear the cause of the said variation of hardness distribution with repeated cycles. It is generally considered that hardening of steel accompanied by plastic deformation is due to strain hardening and ageing effect, while softening to strain softening and thermal recovery. And in case where those hardening and softening arise locally per grain, the distribution width of measured hardness will fluctuate.

Of these, temperature rise of the specimen is considered as a cause of softening by thermal recovery. So the change of surface temperature of specimen in fatigue process was measured with Thermister-thermometer. In Fig. 8 is shown the result of measurement in room temperature, where fatigue test was given on a 0.24%-C steel specimen with stress of 28 kg/mm$^2$ and 3,000 rpm . The rate of temperature rising is little in the earlier stage of fatigue life, but it shows a shrp increase after 10% of fatigue life.

So, the number of revolution was decreased from 3,000 rpm to 33 rpm to prevent the temperature rising of specimen and fatigue test was made, in the process of which hardness was measured in the same way as discribed above. As to a 0.24%-C steel specimen, the fluctuations of mean value, distribution and standard deviation of measured hardness are shown against repeated cycles in Fig. 9. In this case, in spite that temperature rising accompanied by repeated cycles was hardly observed through the fatigue test, there is no difference observed between its measured value and the result shown in Fig. 5. Consequently, it can not be considered that the phenomenon in which distribution width fluctuates with repeated cycles in the late stage of fatigue life is caused by thermal recovery due to the rise of temperature.

Next, in order to examine the effect of hardening due to ageing, measurement was made on Killed steel. The annealed and slowly cooled 0.12%-C Si-Al Killed steel is considered for ageing very difficult to occur, as it contains very little amount of carbon and nitrogen atoms inserted in the space of lattice (2). The result of measurement in the same method as above on this specimen with stress of 28 kg/mm$^2$ and revolution of 3,000 rpm is shown in Fig. 10. In this case also no remarkable difference is observed in the result of measurement compared with Fig. 5, then it is difficult to admit that the main cause of fluctuation of hardness distribution is age-hardening.

Finally, the change of hardness of crystal grain caused by slip lines is examined. Specimens used in the experiment are 0.24%-C steel, after etching its surface with 5%-HNO$_3$-Alcohol Solution, hardness on ferrite grains were measured several times during the fatigue test. The load was 50 gr and the measurement points were about 10 points each step of fatigue test. The mean value and distribution width of measured hardness are shown in the same way as before in Fig. 11. White circle in the figure show the result obtained for the grains with no sign of slip lines, while black dots are one obtained by measuring the grains with the appearance of slip lines in fatigue test. As is clear from the figure, mean value of hardness of the grains with the appearance of slip lines is lower than that of the grain without it. This is considered to be due to the strain softening of grains given rise to by slip.

The following conclusion will be derived from the above examinations. The reason why distribution width of hardness fluctuates with repeated cycles in the late stage of fatigue life is considered that strain hardening and strain softening accompanied by the appearance of slip lines occur alternately in each grain.

## ACKNOWLEDGMENT

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## REFERENCES

(1) R. H. Mozberg, cited in A.Buch's paper, "Fatigue Resistance of Materials and Metal Structural Parts", edited by A.Buch, Pergamon Press, 1964, Warszawa, p.150.

(2) W. C. Leslie and R. L. Rickett, J. Metals, 5 (1953), p.1021.
B. E. Hopkins and H. R. Tipler, J. Iron & Steel Inst., 177 (1954), p.110.

Table 1. Chemical composition of material tested (%)

| Material | C | Mn | Si | P | S | Cu | Al | Ni | Cr |
|---|---|---|---|---|---|---|---|---|---|
| 0.07%C-steel | 0.07 | 0.47 | 0.26 | 0.008 | 0.027 | — | — | — | — |
| 0.24%C-steel | 0.24 | 0.51 | 0.26 | 0.013 | 0.022 | 0.09 | — | — | — |
| 0.12%C-Killed steel | 0.12 | 0.32 | 0.26 | 0.015 | 0.016 | 0.17 | 0.008 | 0.092 | 0.039 |

Table 2. Annealing condition of material tested

| Material | Temperature | Time | Remarks |
|---|---|---|---|
| 0.07%C-steel | 930°C | 1.5 hr | $10^{-5}$ mHg vacuum furnace cooling in furnace |
| 0.24%C-steel | 880°C | 1.5 hr | Ditto |
| 0.12%C-Killed steel | 910°C | 1.5 hr | Ditto<br>cooling rate:5-10 °C/hr |

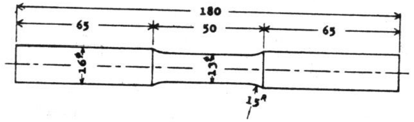


Fig.1 Dimensions of test specimen.

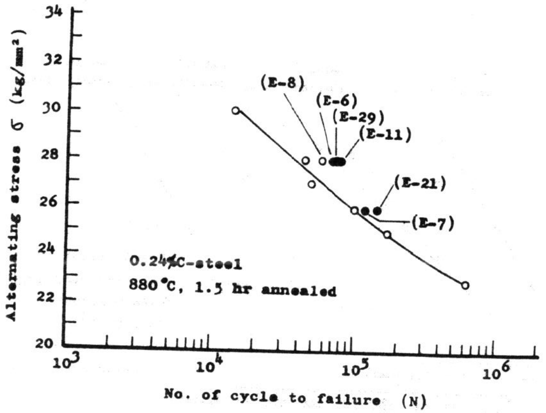
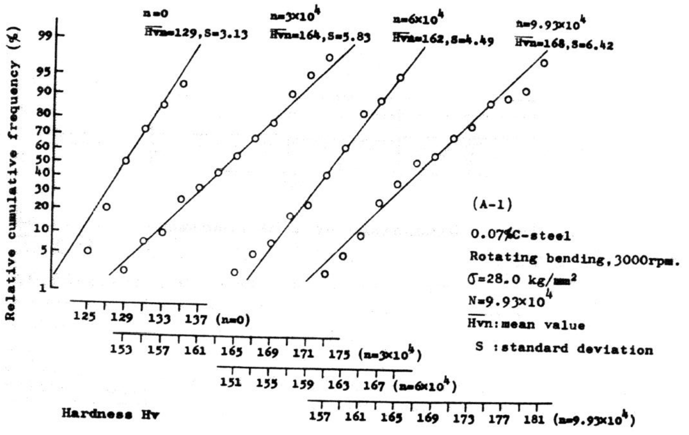
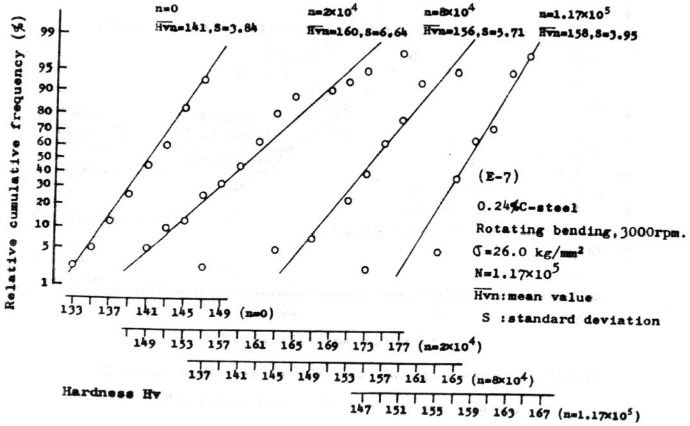


Fig.2 S-N relations for 0.24%-C steel specimen (white dots) and for one subjected to indentations for hardness measurements (black dots).



(a) The case of 0.07%-C steel specimen



(b) The case of 0.25%-C steel specimen

Fig.3 Relative cumulative frequency of distribution of micro hardness plotted on probability paper.

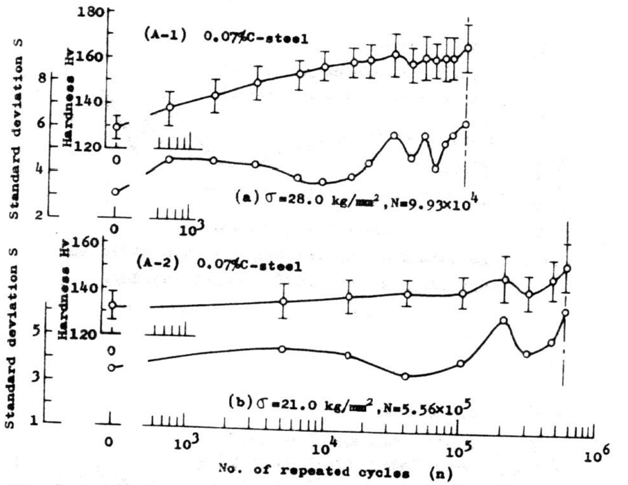


Fig.4 Variation of mean value and standard deviation of hardness distribution with the number of repeated cycles for 0.07%-C steel specimen.

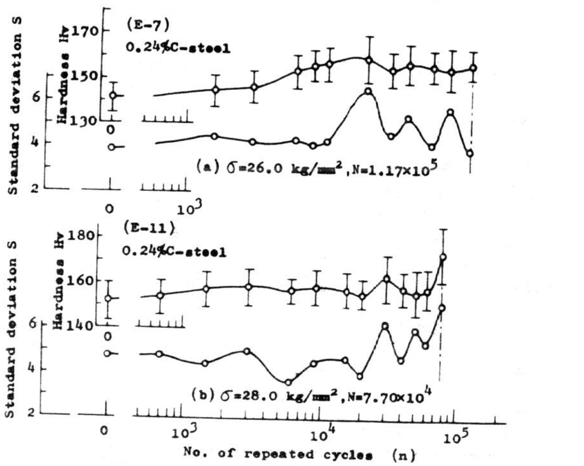


Fig.5 Variation of mean value and standard deviation of hardness distribution with the number of repeated cycles for 0.25%-C steel specimen.

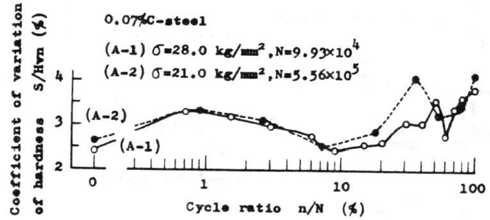


Fig.6 Distribution characteristics in coefficient of variation for 0.07%-C steel specimen.

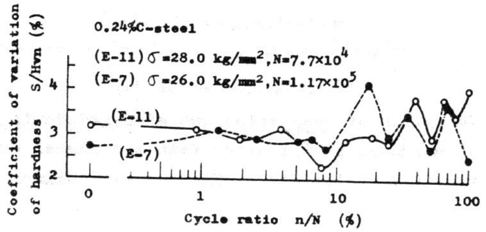


Fig.7 Distribution characteristics in coefficient of variation for 0.24%-C steel specimen.

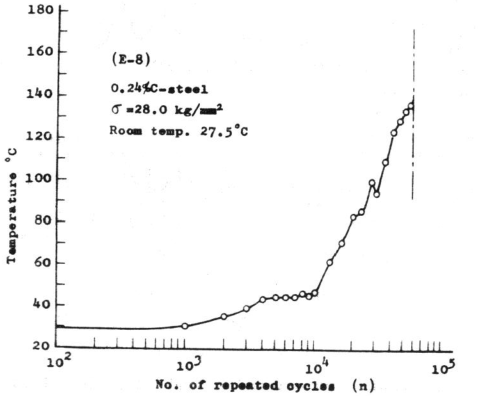


Fig.8 Temperature raise of specimen subjected to repeated stresses of σ =28 kg/mm², 3,000 rpm.

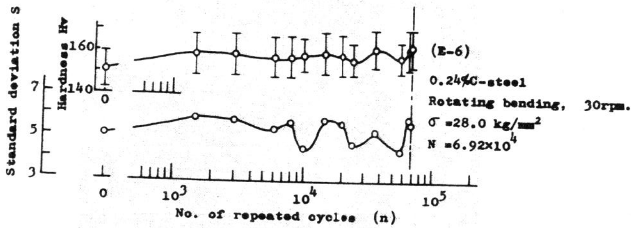


Fig.9 Variation of mean value and standard deviation of hardness distribution with number of repeated cycles of 30 rpm.

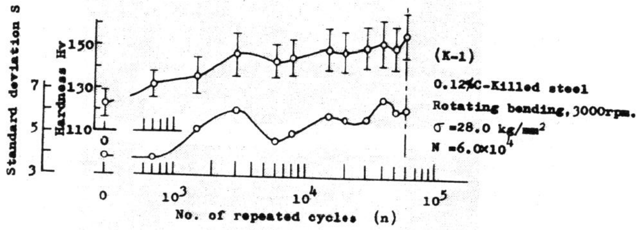


Fig.10 Variation of mean value and standard deviation of hardness distribution with number of repeated cycles for 0.12%-C Killed steel specimen.

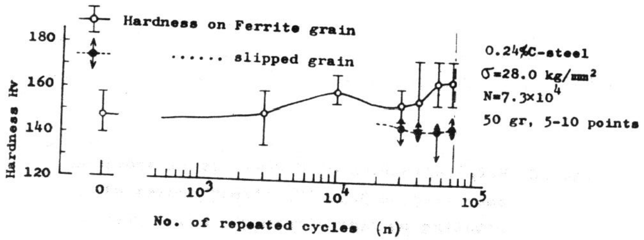


Fig.11 Distribution of hardness measured for ferrite grains. White dots show one for grains with no sign of slip lines, black dots show one for grains with appearance of slip lines.

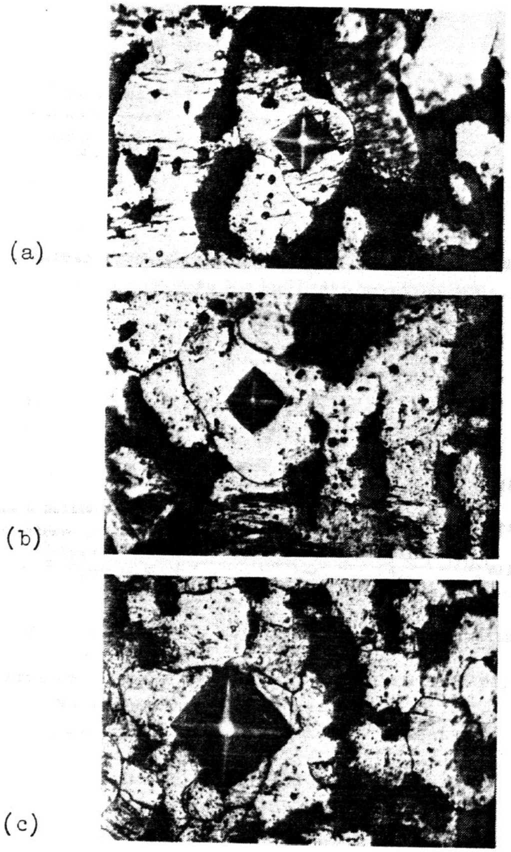


Fig.12 Metallographics of 0.24%-C steel specimen subjected to $3.5 \times 10^4$ stress cycles with rotating bending stress $\sigma = 28.0$ kg/mm². Magn. X600.
(a) and (b) are with a Micro-Vickers indentation of 50 gr load.
(c) is with 200 gr load.