CYCLIC ELASTIC-PLASTIC STRAIN BEHAVIOR AHEAD OF NOTCHES UNDER CYCLIC TENSILE LOAD AND FATIGUE LIFE

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ABSTRACT

The strains ahead of notches in steel plate specimens have been investigated using strain gages in order to find the relationship between the cyclic strains under cyclic tensile load and the fatigue life in the range of 10^5-10^6 cycles. From the cyclic strains measured, the relationships between strain range, mean strain, plastic zone size and the number of cycles, as well as the strain distribution near notches are investigated. Two types of cyclic strain behavior near notch roots have been found ; in one type the mean strain and the plastic zone increase as the number of cycles increases and in another type the mean strain and the plastic zone remain constant with increasing cycles. These two types of cyclic strain behaviors show fatigue responses near notches under cyclic tensile load. The experimental results and their discussion are presented.

KEYWORDS

Cyclic strain behavior, Strain range, Mean strain, Increasing mean strain, Constant mean strain Notch root radius, Strain concentration, Strain distribution, Medium cycle fatigue

INTRODUCTION

Fatigue strength in high cycle regions during stress control test has been estimated using the S_R-N_f curve and the K-K_f relation , where S_R is the stress range and N_f is the number of cycles until smooth specimens fracture, K is the elastic stress concentration factor of notched specimens and K_f is the fatigue strength reduction factor for notched specimens. Recently, the linear notch mechanics (Nishitani, 1987) has been presented to estimate the fatigue limit of notched specimens. Fatigue strength in low cycle region during the strain control test has been estimated using the ϵ_R-N_f curve and K_ϵ (Neuber, 1961), where ϵ_R is the cyclic strain range and K_ϵ is the strain concentration factor of notches. The fatigue strength of notches during the stress control test in medium cycle regions, where the fatigue life is in the range of 10^5-10^6 cycles, contain complicated phenomena regarding stress or strain behavior ahead of notches, and a proper method to estimate the fatigue life has seldom been presented. We think that the fatigue life of notched specimens is controlled by the maximum strain at notch roots and by the strain distribution near notches. In this study, cyclic elastic-plastic strain behavior ahead of notches in steel plate specimens under cyclic tensile load is investigated using strain gages, and some experimental results and their discussion are presented.

MATERIALS, SPECIMENS AND EXPERIMENTAL PROCEDURES

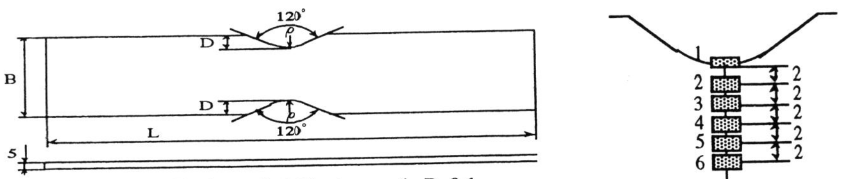
The chemical composition and the mechanical properties of the material used are shown in Table 1 and Table 2 respectively. The specimens are shown in Fig. 1. (a) and the notches are V-notch with 120 degree flank angles. One series of used specimens are specimens in which the notch root radiuses are 2, 4, 10 mm with constant notch depth of 6 mm (Shingai, 1995a, 1996a, 1996b) and another series are specimens in which the notch depths are 10, 11, 18 mm with constant notch root radius of 8 mm. Strain gages with gage length of 0.2 mm are attached to the notch roots, and strain gages with gage length of 1 mm are attached ahead of the notch root at distance of 2 mm as shown in Fig. 1. (b). The cyclic tensile fatigue test was conducted with MTS fatigue test machine and the strains were recorded continuously using dynamic strain recorder.

Table 1. Chemical composition

C	Si	Mn	P	S	Ni	Cr	Cu
0.24	0.22	0.5	0.012	0.016	0.07	0.15	0.13

Table 2. Mechanical properties (annealed 1 hour at 880°C)

Modulus of elasticity E	199 GPa
Yield stress σ_y	273 MPa
Tensile strength σ_B	457 MPa
Elongation δ	38 %



L=200, B=40, D=6, ρ =2, 4, 10, stress ratio R=0.1

(a) L=290, B=60 or 72, ρ =8, D= 10, 11, 18, stress ratio R=0 (b)

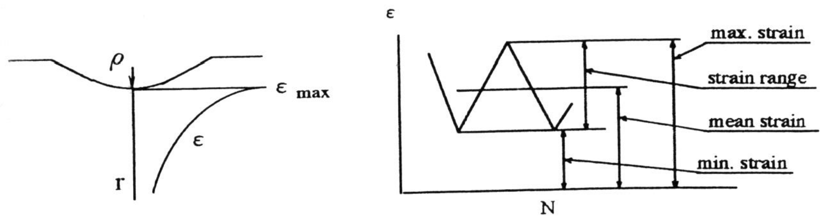
Fig.1. Dimensions of the specimen and positions of the strain gages (all dimensions in mm)

EXPERIMENTAL RESULTS

Fig. 2. (a) shows the definitions of strain, ε_{max}, ε, the notch root radius, ρ and the distance from the notch root, r. Fig.2. (b) shows the definitions of maximum strain, strain range, mean strain and minimum strain.

THE RELATIONSHIP BETWEEN THE NET STRESS RANGE AND THE NUMBER OF CYCLES UNTIL SPECIMENS FRACTURE

All fatigue data tested were plotted on the S_R-N_f diagram of Fig. 3 in which S_R is the range of net stress and N_f is the number of cycles until specimens fracture. The range of N_f is between 10^5 cycles to 10^6 cycles, which is the medium cycle region. In Fig. 3, two types of cyclic strain behavior has been found ; in one type the mean strain increases as the number of cycles increases and in other type the mean strain remains constant with increasing cycles. These two types are expressed as I.M.S. and C.M.S. respectively. The transition region between these two types of strain behaviors may exist at N_f of about 2.5×10^5 cycles and at S_R of about 250 MPa .



(a) (b)

Fig. 2. Definitions

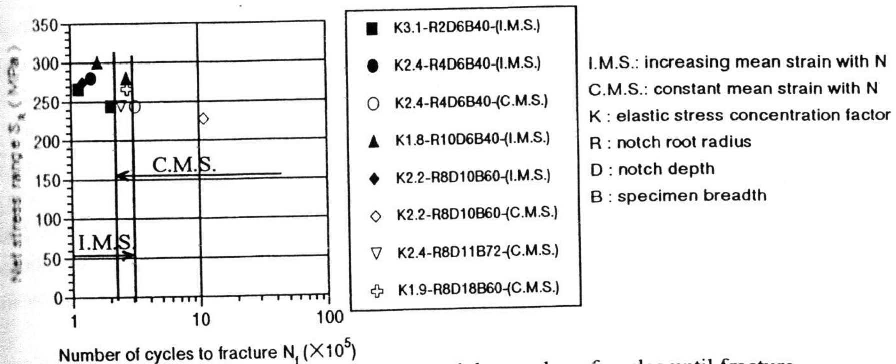


Fig. 3. Relation between the net stress range and the number of cycles until fracture

BEHAVIOR OF CYCLIC STRAIN RANGE AND MEAN STRAIN NEAR NOTCHES

Typical cyclic behavior of the specimens tested are shown in Fig. 4., 5.1., 5.2. In these figures, strain ranges str1, str2 etc. mean the strain ranges at the positions of the strain gages attached to the specimens and 1 is the strain at the notch roots and 2, 3 etc. are strains ahead of notch roots at distance of 2 mm, 4 mm, from the notch roots as shown in Fig. 1. Also the mean strains stm1, stm2 etc. mean the mean strain at each position of the strain gages. In case of the specimen (S274 MPa, K2.2/R8) in Fig.4, the mean strains increase as the number of cycles increases (I.M.S.). The strain range at the notch root increases initially and keeps a nearly constant value of about 0.4 % until crack initiation. The mean strain at notch root increases steadily from 0.35 % to about 1.6 % at the crack initiation as the number of cycles increases . Strains ahead of notches have similar changes, but the changes are small. Therefore, in case of I.M.S. the strain fields near notches change with increasing number of cycles ; in other words the responses of strain field near notches change during fatigue cycles.

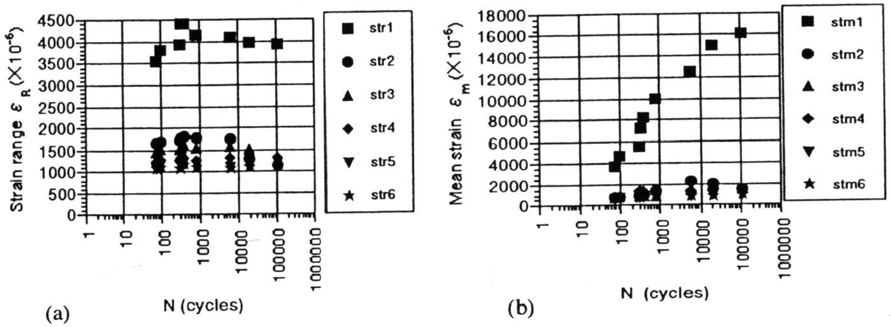


Fig. 4. Cyclic behavior of strain range and mean strain ahead of the notch with increasing number of cycle for the specimen K2.2-S274-R8D10B60 (I.M.S.), (N_f=125851 cycles)

In the case of two specimens with different notch root radiuses (S245MPa, K2.4/R4 and S244, K2.4/R8) of Fig.5.1and Fig. 5.2, cyclic strain behaviors are nearly constant mean strains with an increasing number of cycles (C.M.S.). In case of the notch root radius, 4 mm, in Fig. 5.1, the strain range at the notch root, 0.34 %, does not change with an increasing number of cycles and the mean strain at the notch root increases a little at first, but soon becomes a constant value, 0.62 %, with an increasing number of cycles. In case of the notch root radius of 8 mm in Fig. 5.2, both strain range and mean strain at the notch root remain constant values of 0.35 % and 1.05 % respectively until crack initiation. Therefore, in case of C.M.S. the strain fields near notches don't change with an increasing number of cycles, or in other words the responses of strain field near notches are the same during fatigue cycles.

Next in case of the I.M.S. and C.M.S. mentioned above, the author investigates the strain concentration factor, K_ε, the strain distribution, ε -r, the relative strain ratio distribution, $\varepsilon / \varepsilon_{max}$-

r/ ρ, and the plastic zone size in front of notches which have simply been defined based on the assumption that the material yields when the maximum principal strain in front of notches exceeds the uniaxial yield strain without considering the yielding criteria in biaxial stresses in front of notches. Fig. 6 shows the relationship between the strain concentration factor and the number

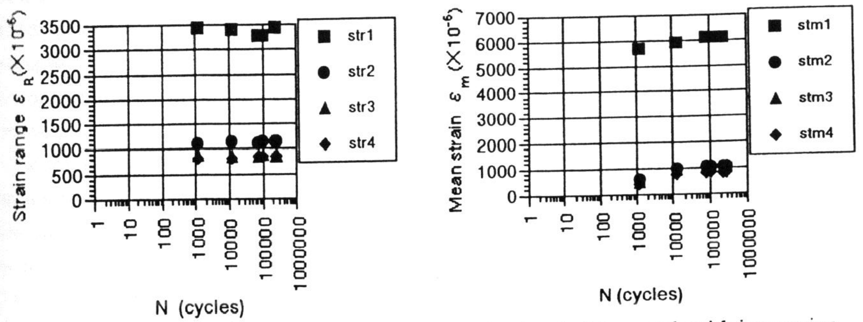


Fig. 5.1. Cyclic behavior of strain range and mean strain ahead of the notch with increasing number of cycles for the specimen K2.4-S245-R4D6B40(C.M.S.), (N_f=317000 cycles)

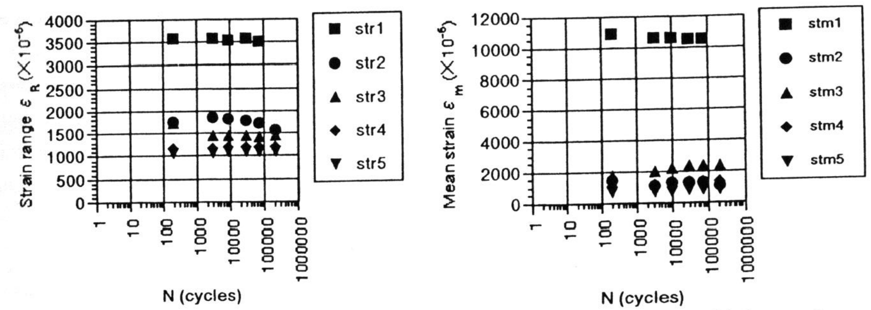


Fig. 5.2. Cyclic behavior of strain range and mean strain ahead of the notch with increasing number of cycles for the specimen K2.4-S244-R8D11B72(C.M.S.), (N_f=249500 cycles)

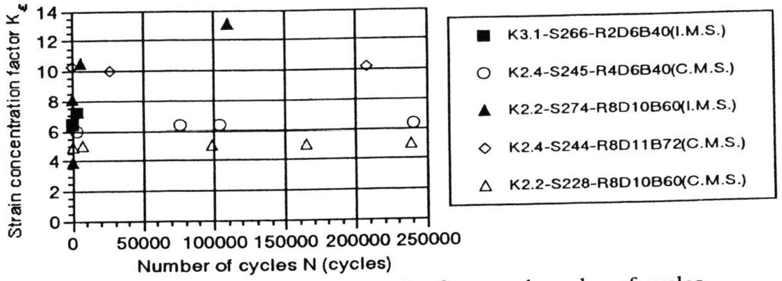
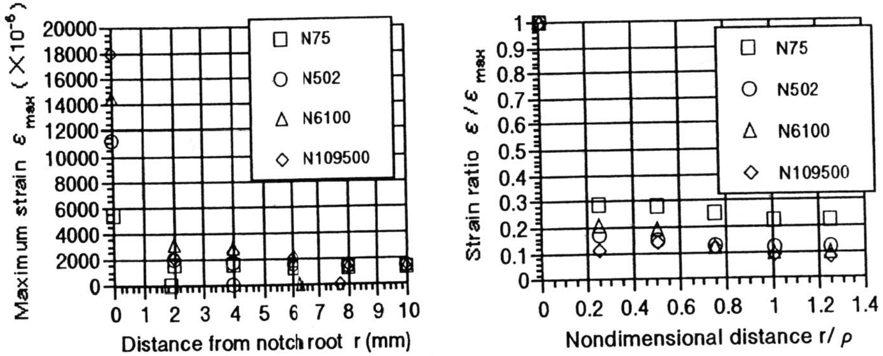


Fig. 6. Relation between strain concentration factor and number of cycles

of cycles where the strain concentration factor have been defined as the division of the maximum strain at notch roots by the net strain based on the net section area. In Fig. 6, in case of I.M.S. the strain concentration factors increase with the number of cycles and in case of C.M.S. the strain concentration factors are nearly constant with increase in the number of cycles.

Fig. 7 shows the changes in strain distribution, strain ratio distribution and plastic zone size with an increasing number of cycles in I.M.S. corresponding to Fig. 4. It has been found that the maximum strain at the notch root and the plastic zone size ahead of the notch root (shown on the x-axis) increases with an increasing number of cycles, and strain ratio distributions near the notch become steeper with an increasing cycles. In case of C.M.S. of Fig. 8.1. and 8.2.(corresponding to Fig. 5.1, 5.2 respectively), it has been found that the maximum strains at notch roots and the plastic zone sizes are constant with an increasing number of cycles, and the strain ratio distributions also remain constant with increase in the number of cycles. It seems that both strain distributions near notches of Fig. 8.1 and Fig. 8.2 are similar in spite of different notch root radiuses since strain ratios are 0.20 and 0.18 respectively at the nondimensional distances of 0.5 in Fig. 8.1 and 0.25 in Fig. 8.2 which correspond to the distance from notches of 2 mm. The strain ranges of Fig. 5.1 and Fig. 5.2 are nearly same since these values are 0.34% and 0.35% respectively. Therefore, the difference between the fatigue lives of Fig. 8.1 and Fig. 8.2 is small.

The author thinks that the transition from C.M.S. to I.M.S. may depend on the cyclic net stress level, the elastic stress concentration factor , the notch root radius and the stress-strain curve of the material. This reason is as follows ; the maximum strain at the notch root radius is determined by Neuber's equation (Neuber, 1961), $K_\varepsilon = K^2/K_\sigma$, in which K_ε is the strain concentration factor and K_σ is the stress concentration factor. K_ε and K_σ depend on the stress-strain curve. The strain distribution ahead of a notch depends mainly on the net stress level and the notch root radius according to our work (Shingai, 1996b).

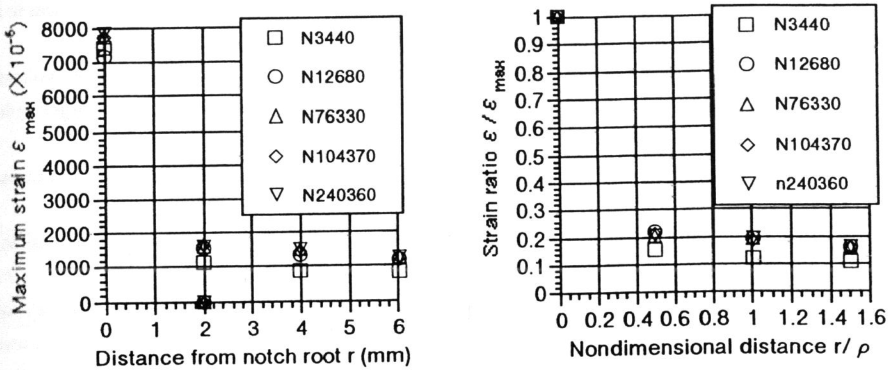


Note : Symbols on the x-axis show the plastic zone size.

(a) (b)

Fig. 7. Relation of strain distribution, strain ratio distribution and plastic zone size with increasing number of cycles for the specimen K2.2-S274-R8D10B60(I.M.S.), (N_f=125851cycles)

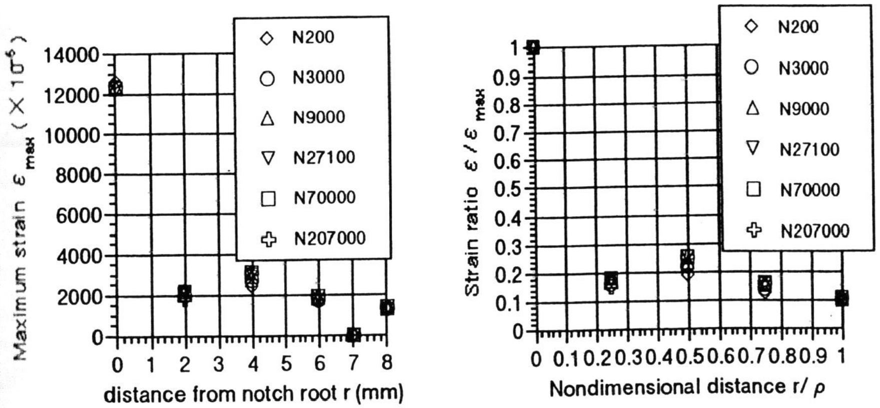
In the fatigue design of notched plates under the load control conditions, the author thinks that in the cycle region of C.M.S., the method using the S_R-N_f curve and the K-K_f curve based on the stress range in high cycle fatigue can be applied to estimate fatigue life and that in the cycle region of I.M.S., the ε_R-N_f curve based on the strain range in the low cycle fatigue and the effect of increasing mean strain on fatigue life should be considered to estimate fatigue life. We are studying this area further.



Note : Symbols on the x-axis show the plastic zone size.

(a) (b)

Fig. 8.1. Relation of strain distribution, strain ratio distribution, and plastic zone size with increasing number of cycles for the specimen K2.4-S245-R4D6B40(C.M.S.), (N_f=317000cycles)



Note : Symbols on the x-axis show the plastic zone size.

(a) (b)

Fig.8.2.Relation of strain distribution, strain ratio distribution, and plastic zone size with increasing number of cycles for the specimen K2.4-S244-R8D11B72(C.M.S.), (N_f=249500 cycles)

CONCLUSIONS

From the experimental data and their discussion above, the following conclusions can be drawn.

1. In medium fatigue cycles region where the fatigue life is in the range of 10^5-10^6 cycles, two types of the strain behavior near notches have been found. One type is strain behavior where the mean strain at the notch roots and near notches increases with an increase in the number of cycles (I.M.S.) and another type is strain behavior where the mean strain at the notch roots and near the notches is nearly constant with an increase in the number of cycles (C.M.S.).
2. In case of I.M.S., the relative strain ratio distributions ahead of notches become steeper with an increase in the number of cycles and the plastic zone sizes in front of notches become larger with an increasing cycles.
3. In case of C.M.S., the relative strain ratio distribution and the plastic zone size ahead of notches are nearly constant with an increase in the number of cycles.
4. In both cases of the I.M.S. and C.M.S., the strain range is nearly constant during the fatigue cycles.
5. In case of C.M.S., it seems that both fatigue lives are nearly same when their strain ranges and strain distributions near notches regarding two specimens with different notch root radius are similar respectively.
6. In the fatigue design of the notched plate under the load control condition, the author thinks that in the cycle region of C.M.S., the method using S_R-N_f curve and K-K_f curve based on the stress range in high cycle fatigue can be applied to estimate fatigue life and that in the cycle region of I.M.S., the ε_R-N_f curve based on the strain range in the low cycle fatigue and the effect of increasing mean strain on fatigue life should be considered to estimate fatigue life.

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