Estimatimation of Low Cycle Fatigue Strength of Steels in Strain Controlled Cycling Condition

T. Hotta, S. Kanazawa, T. Ishiguro, N. Ishii, S. Sekiguchi
Product Research and Development Laboratories,
Nippon Steel Corporation, Tokyo Japan

1. Introduction

In the study of low cycle fatigue behavior, Manson-Coffin's linear relationships have been well recognized. However, some experimental results reveal a new evidence which is a divergence from Manson-Coffin's linear relationship between plastic strain range and number of cycles to failure.

The authors attempt to examine the validity of Manson's estimation method for steels from our strain controlled low cycle fatigue tests. And, it is the aim of this paper to propose the new estimation method of low cycle fatigue strength of steels.

2. Test Method

Steel used in this experiment ranged from low carbon steel to ultra high tensile strength steel for rocket use. The tensile test specimens were of JIS No. 4 subsize type and low cycle fatigue test specimens were of hourglass type with their theoretical elastic stress concentration factor Kt of 1.06. A servo type low cycle fatigue tester of 10 tons in capacity was used for this purpose. A diametral strain of an hourglass type specimen was measured by applying the measurement probes of a diametral strain gauge to the minimum crosssectional region of the specimen. Strain waves were controlled approximately by triangular waves with their strain ratio being −1. From an preliminary experiment the strain cycling rate was so determined to be 4×10^{-3}/sec as to minimize the effect of strain rate.

The longitudinal strain ranges are calculated from a diametral strain by the equation ;

$$\epsilon_{tr} = 4\ln\frac{d_c}{d_0} + (1-2\nu)\frac{\sigma_R}{E} \qquad \text{(1)}$$

$$\epsilon_{er} = \frac{\sigma_R}{E} \qquad \text{(2)}$$

$$\epsilon_{pr} = 4\ln\frac{d_c}{d_0} - \frac{2\nu}{E}\sigma_R \qquad \text{(3)}$$

where the symbols define the following quantities ;

ϵ_{tr} : Longitudinal Total Strain Range

ϵ_{pr} : Longitudinal Plastic Strain Range
ϵ_{er} : Longitudinal Elastic Strain Range
d_o : Initial Diameter of Specimen at Minimum Crosssection
d_c : Diameter of Compressed Specimen at Minimum Crosssection
ν : Poisson's Ratio (0.3)
E : Young's Modulus (17,000 kg/mm^2 for Cast Iron, 21,000 kg/mm^2 for Other steels)
σ_R : True Stress Range in Stable Condition (kg/mm^2)

3. Experimental Results and Discussion

The ultimate tensile strength σ_u of the test materials used in this experiment greatly varies from approximately 36 kg/mm^2 for low carbon steel to 200 kg/mm^2 for ultra high tensile strength steel. The static fracture ductility ϵ_f which is a dominant factor govering strain controlled low cycle fatigue strength in a short life region, also widely ranges from 0.01 for cast iron to 1.68 for stainless steel.

The results of strain controlled low cycle fatigue tests are shown in ϵ-N diagram on log-log coordinates. The abscissas indicate the number of cycle to failure N_f, and/or the number of cycles to crack initiation N_c, observed through a magnifying glass of 1.5 magnifications. The ordinates indicate ϵ_{tr}, ϵ_{pr} and/or ϵ_{er}, each obtained from Eq.'s (1), (2) and (3), respectively.

From all test results, the following relationships between ϵ_{er} and N_f may be verified.

$$\epsilon_{er} \cdot N_f^{k_{fe}} = C_{fe} \quad \cdots\cdots (4)$$

However, it will be noticed that there are two groups of steels, one for which the equation (5) for ϵ_{pr} in terms of N_f hold over whole long life regions, another

$$\epsilon_{pr} \cdot N_f^{k_{fp}} = C_{fp} \quad \cdots\cdots (5)$$

for which Eq.'s (5) hold over only short life regions, and hence over long life regions Eq.'s (5) become deviated. The authors tentatively call these latter phenomena as kink phenomena, and the points at which linearity break down, as kink points.

Low cycle fatigue strength of steels estimated by Manson's universal slope or four points method tends in many cases to overestimate the true low cycle fatigue strength of steels, hence giving risky results.

Steels are categorized into two groups, one for which the plastic strain range and the life obey Manson-Coffin's linear relationship over the whole life region, and another for which the plastic strain range and life do not follow Manson-Coffin's linear relationship over the whole life region due to substantial lowering of the plastic strain. The plastic strain range of latter group, therefore, becomes much deviated near $N_f=10^4$ from the estimated point.

In the case of kink-exhibiting steel, it is the total strain range, rather than the plastic strain range, that is linear in life. Therefore it seems appropriate to use the total strain range-life relation in making an estimation of low cycle fatigue strength of such steels.

The extension of the elastic line in low cycle region also lies on high cycle fatigue curve. Thus it is made clear that the whole fatigue curve in low and high cycle region of kink-exhibiting steel consists of two straight lines, namely that of the total strain range versus number of cycles and that of the elastic strain range versus number of cycles, both being expressed in logarithmic scale.

Therefore, it is desirable to estimate the low and high cycle fatigue strength of steels according to the following formula.

For steels which satisfy Manson-Coffin's linear relationship ;

$$\epsilon_{tr} = C_{fp} \cdot N_f^{-k_{fp}} + C_{fe} \cdot N_f^{-k_{fe}} \quad \cdots\cdots (6)$$

For steels which show a divergence from Manson-Coffin's linear relationship ;

in the low cycle range

$$\epsilon_{tr} = C_{ft} \cdot N_f^{-k_{ft}} = (C_{fe} + C_{fp}) \cdot N_f^{-k_{ft}} \quad \cdots\cdots (7)$$

in the intermediate and high cycle range

$$\epsilon_{tr} = C_{fe} \cdot N_f^{-k_{fe}} \quad \cdots\cdots (8)$$

On the other hand, the relationship between material constant in low cycle fatigue and tensile properties is given in good approximation as follows ;

$$C_{fp} = 0.715\,\epsilon_f^{0.705} \quad \cdots\cdots (9)$$

$$C_{fe} = 1.39 \times 10^{-4} \sigma_u \quad \cdots\cdots (10)$$

$$k_{fp} = 0.474 n_f + 0.467 \quad \cdots\cdots (11)$$

$$k_{fe} = 0.056 + 1.29/(\sigma_u - 26.3) \quad \cdots\cdots (12)$$

$$k_{ft} = 0.862 n_f + 0.353 \quad \cdots\cdots (13)$$

where the symbols define the following quantities ;

C_{fp} : Constant in ϵ_{pr} versus N_f Curve
C_{fe} : Constant in ϵ_{er} versus N_f Curve
C_{ft} : Constant in ϵ_{tr} versus N_f Curve
k_{fp} : Exponent in ϵ_{pr} versus N_f Curve
k_{fe} : Exponent in ϵ_{er} versus N_f Curve
k_{ft} : Exponent in ϵ_{tr} versus N_f Curve
ϵ_f : True Fracture Ductility
σ_u : Nominal Ultimate Tensile Strength (kg/mm^2)
n_f : Work Hardening Exponent at Necking Stage

Steel that do not exhibit the kink phenomena in ϵ_{pr}-N_f diagrams, and satisfy Manson-Coffin's linearity, have tensile strength less than 60 kg/mm^2. Their metallographic structures are ferrite,

ferrite-pearlite and austenite. The fatigue curve of these steels in the low and high cycle range is given in good approximation from Eq.'s (6), (9), (10), (11) and (12) as follows;

$$\varepsilon_{tr} = 0.715\varepsilon_f^{0.705} \cdot N_f^{-(0.414 n_f + 0.467)} + 1.39\times10^{-4}\sigma_u \cdot N_f^{-\{0.056 + 1.29/(\sigma_u - 26.3)\}} \quad \cdots\cdots (14)$$

On the other hand, steels that exhibit the kink phenomena have tensile strength greater than 60 kg/mm² and their metallographic structures are bainitic and martensite. Nodular graphite cast iron also exhibits the kink phenomena. The fatigue curve of these steels consist of two straight lines as follows ;

in the low cycle range from Eq.'s (7), (9), (10) and (13)

$$\varepsilon_{tr} = (1.39\times10^{-4}\sigma_u + 0.715\varepsilon_f^{0.705}) N_f^{-(0.862 n_f + 0.353)} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (15)$$

in the intermediate and high cycle range from Eq.'s (8), (10) and (12)

$$\varepsilon_{tr} = 1.39\times10^{-4}\sigma_u \cdot N_f^{-\{0.056 + 1.29/(\sigma_u - 26.3)\}} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (16)$$

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