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Focussed on Multiaxial Fatigue and Fracture

Fatigue strength of SS400 steel under non-proportional loading

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ABSTRACT. This study discusses fatigue properties of low carbon steel, type SS400 steel, under non-proportional loading. Multiaxial fatigue tests under proportional and non-proportional loading conditions with various stress amplitudes were carried out using a hollow cylinder specimen at room temperature. In the test, three types of stress paths were employed. They are a push-pull, a reversed torsion and a circle loading. The circle loading is a cyclic loading combined the push-pull and the reversed torsion loading in which axial and shear stress waveforms have 90 degrees phase differences. From the obtained test results, poor evaluations of failure life under non-proportional loading are indicated when the life is correlated by the equivalent strain range based on von Mises Δεeq and the non-proportional strain range ΔεNP. A modified strain parameter is presented which can evaluate the failure life in high and low strain levels under non-proportional loading.

KEYWORDS. Fatigue; Multiaxial stress; Non-proportional loading; Life evaluation; Carbon steel.

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INTRODUCTION

Non-proportional loading of which directions of principal stress and principal strain are changed in a cycle occurs in various structures such as machinery for construction and transportation. In studies of multiaxial fatigue under non-proportional loading conditions; it has been reported that failure life is reduced accompanying with an additional hardening depending on both strain path and material [1-12]. Itoh et al. have carried out series of multiaxial low cycle fatigue (LCF) tests under non-proportional loading conditions to examine properties of cyclic deformation and failure life [10-12]. They presented a strain parameter for life evaluation under non-proportional loading; a non-proportional strain range $\Delta\varepsilon_{NP}$; which includes a non-proportional factor taking into account the effect of loading path and a material constant related to the additional hardening due to non-proportional loading [4;10-12]. However; there is few studies discussing failure life in high cycle region and fatigue strength under non-proportional loading [13;14]. In order to ensure reliability and safety of machinery; evaluating models for non-proportional loading including the high cycle region is required.

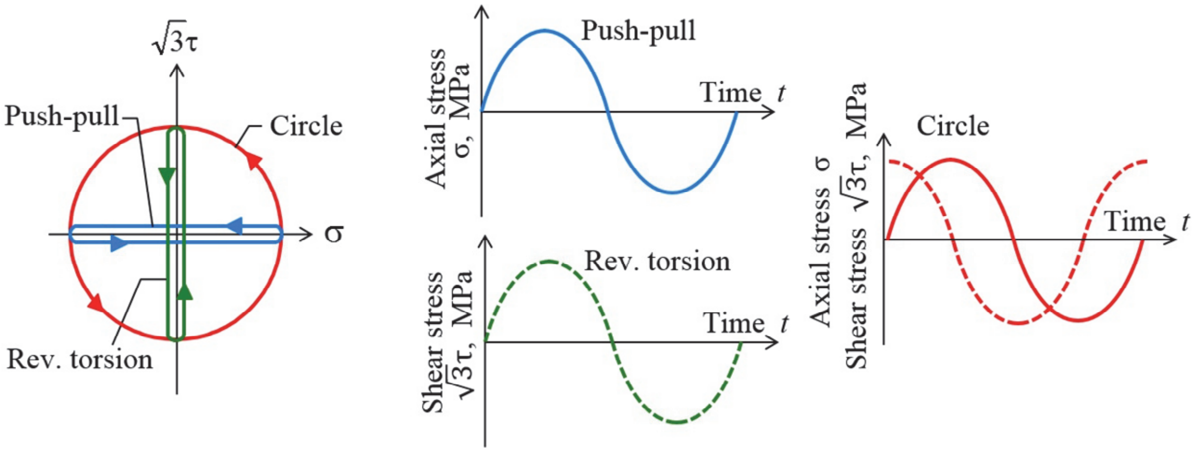
In this study; multiaxial fatigue tests under proportional and non-proportional loading conditions were carried out in the low stress level to discuss fatigue strength. For evaluation of failure life in the high cycle region; an applicability of equivalent stress and strain ranges based on von Mises and $\Delta\varepsilon_{NP}$ is discussed and $\Delta\varepsilon_{NP}$ is also modified to be suitable strain range for life evaluation.

TEST MATERIAL AND EXPERIMENTAL PROCEDURE

Material tested was rolled steel for general structure; type SS400 steel (A283 GRADE D for ASTM; St 44-2 for DIN). A hollow cylinder specimen with 12mm outer-diameter; 9mm inner-diameter in a gauge part is used. An electrical servo controlled hydraulic fatigue testing machine for push-pull and reversed torsion loadings of which maximum push-pull loading and torque are ±50 kN and ±500 N·m was employed as testing machine.

Load controlled fatigue tests were carried out at room temperature. Stress paths were a push-pull; a reversed torsion (rev. torsion) and a circle loading. Fig. 1 shows the stress paths and the stress waveforms. The push-pull and the rev. torsion loading tests are proportional loading tests in which principal directions of stress and strain are fixed. The circle loading test is non-proportional loading test in which axial stress and shear stress have 90 degrees sinusoidal out-of-phase difference. In the circle loading test; axial and shear stress ranges are the same value based on von Mises; $\Delta\sigma = \sqrt{3}\,\Delta\tau$.

Number of cycles to failure (failure life) N_f was determined as the cycle at which a crack occurred on the surface of test specimen. The crack size is big enough to be checked by looking and this test is controlled by loading. Therefore; N_f can be considered as the cycle at which test specimen ruptured.



(a) Stress path

(b) Stress waveform

Figure 1: Stress path and stress waveform.

EXPERIMENTAL RESULTS AND DISCUSSION

Evaluation of Failure Life with Equivalent Stress and Strain

Fig. 2 shows a correlation of failure life with an equivalent stress amplitude based on von Mises $\Delta\sigma_{eq}/2$. Failure life can be correlated by a unique line independent of loading path in the stress region over the fatigue strength σ_w. In the load controlled test; failure life in the circle loading test tends to be longer than those in the push-pull and rev. torsion loading tests. The strain range in the circle loading test becomes smaller in comparison with that in the push-pull loading test at the same stress range because of additional hardening caused by non-proportional loading. In addition; it is known that failure life in the circle loading test is smaller than that in the push-pull loading test at same strain range due to non-proportional loading. In this stress level and the material of SS400; a relative good agreement of data correlations may be resulted from that the additional hardening is balanced with the reduction in failure life.

Fatigue strength in the circle loading test σ_w^{CI} (150MPa) is lower than that in others σ_w^{PP} (175MPa). Fig. 3 shows observations of specimen surface in the push-pull and the circle loading tests at stress amplitude level around the fatigue strengths; $\Delta\sigma_{eq}/2$=200; 175 and 150MPa. The observed location was set at the sufficient distances from a main crack which contributes directly to N_f. In the push-pull loading test; the roughness caused by local plastic deformation can be observed clearly on the specimen surface only at $\Delta\sigma_{eq}/2$=200MPa. In the circle loading test; on the other hand; the remarkable roughness can be observed at $\Delta\sigma_{eq}/2$=200 and 175MPa in comparison with those in the push-pull loading test at each equivalent stress amplitude; which may be resulted from the increase in the number of activated slip systems due to the rotation of principal direction of stress under non-proportional loading. The roughness leads to more chance of initiation of microcracks and the earlier crack initiation. Consequently; the surface roughness causes reduction of the fatigue strength in the circle loading test.

Fig. 4 is the failure life correlated by an equivalent total strain range based on von Mises $\Delta\varepsilon_{eq}$. The strain ranges used are those at the cycle of $0.5N_f$ in experiments. In this figure; the bold solid line is drawn by a universal slope curve [16] based on the experimental data in the push-pull loading test. The universal slope curve is given by

$$\Delta\varepsilon_{eq} = AN_f^{-0.12} + BN_f^{-0.6} \qquad (1)$$

where the coefficients A and B are equated as $3.5\sigma_B/E$ and $\varepsilon_f^{0.6}$ according to the definition of the universal slope method. E; σ_B and ε_f are Yong's modulus; a tensile strength and an elongation; respectively. In this study; A is put as the mechanical properties obtained from the tensile test but B is defined to fit the universal slope curve to the data of the push-pull loading test. In LCF region; failure life in the rev. torsion loading test is underestimated and conversely that in the circle loading test is overestimated out of the factor of 2 band. The same tendency of failure life was shown in the previous study of strain controlled multiaxial LCF test [11]; therefore it suggests that the failure life and the non-proportionality are not affected by the difference in the test control of strain or stress for the tested material. In the high cycle fatigue region; with decrease in strain range; failure life in the circle loading test approaches to that in the push-pull loading test. This trend indicates that the effect of non-proportional loading on failure life is decreased in the lower strain level; which will be mentioned in next.

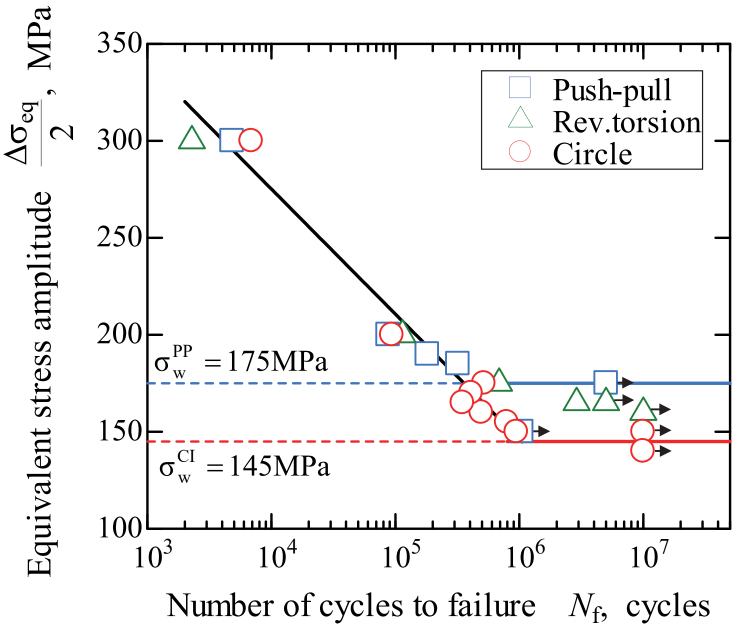


Figure 2: Correlation of N_f with equivalent stress amplitude based on von Mises.

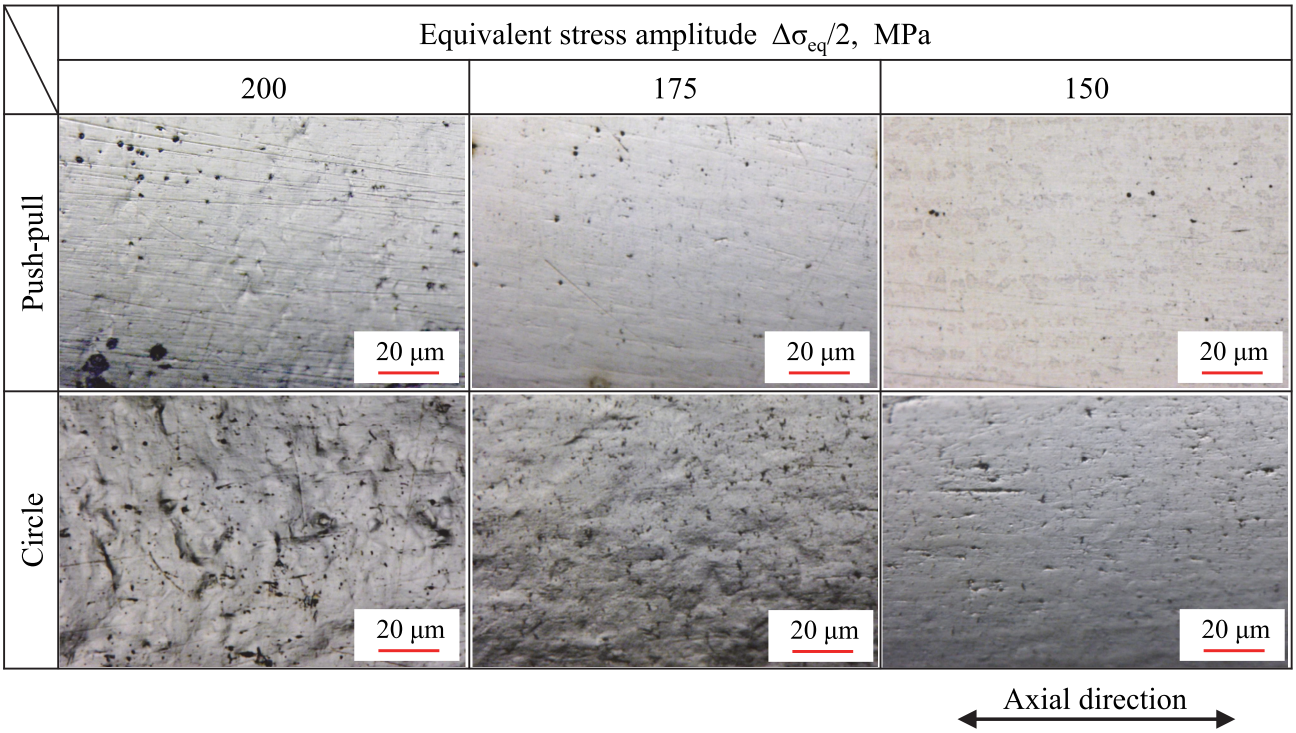


Figure 3: Observation of specimen surface after fatigue tests at $\Delta\sigma_{eq}/2$=200MPa; 175MPa and 150MPa.

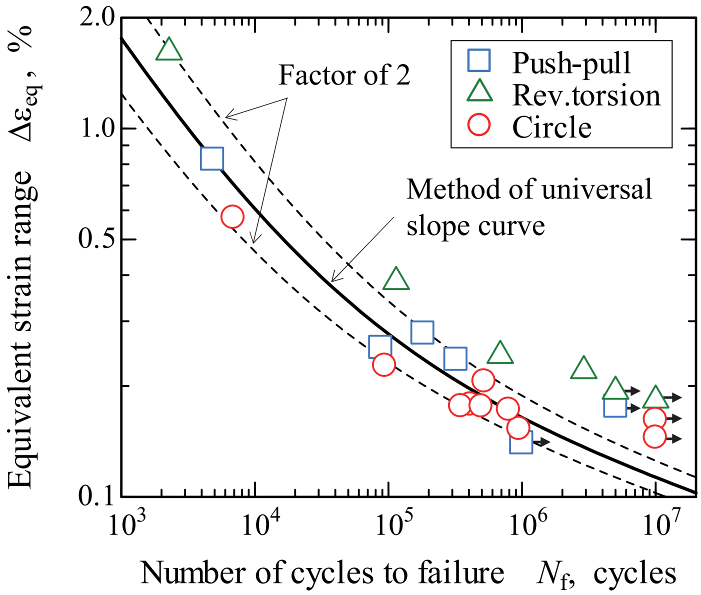


Figure 4: Correlation of N_f with $\Delta\varepsilon_{eq}$.

Applicability of Non-proportional Strain Range for Life Evaluation

Itoh et al. have reported that the large reduction in failure life has a close relation with the strain path and the material [4;6;7;10;11] and they also proposed the non-proportional strain range $\Delta\varepsilon_{NP}$ for life evaluation defined as

$$\Delta\varepsilon_{NP} = (1+\alpha f_{NP})\Delta\varepsilon_{eq} \qquad (2)$$

where $\Delta\varepsilon_{eq}$ is the maximum principal strain range under non-proportional loading which can be calculated by ε and γ. α and f_{NP} are the material constant and the non-proportional factor; respectively. The former is the parameter related to the additional hardening due to non-proportional loading and the latter is the parameter expressing the intensity of non-proportional loading. The value of α is the ratio to fit N_f in the circle loading test to that in the push-pull loading test at the same $\Delta\varepsilon_{eq}$. In this study; the value of α for SS400 is put $\alpha = 0.59$. f_{NP} is defined as

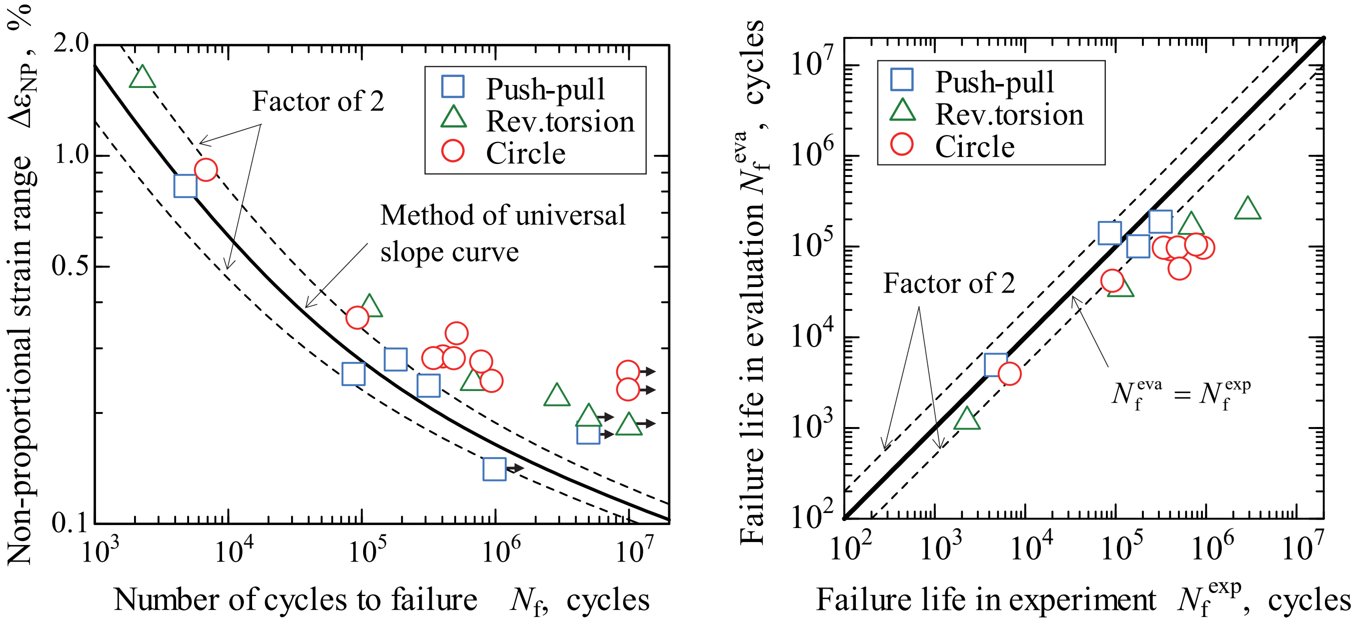
$$f_{NP} = \frac{\pi}{2\varepsilon_{I\max} \cdot L_{path}} \int_C \left| \boldsymbol{e}_I \times \boldsymbol{e}_R \, \varepsilon_I(t) \right| ds \tag{3}$$

where $\varepsilon_I(t)$ is the maximum absolute value of principle strain at time t and $\varepsilon_{I\max}$ is the maximum value of $\varepsilon_I(t)$ in a cycle. $\boldsymbol{e}_I$ and $\boldsymbol{e}_R$ are unit vectors for $\varepsilon_{I\max}$ and $\varepsilon_I(t)$; ds the infinitesimal trajectory of the strain path. L_{path} is the whole strain path length during a cycle and "×" denotes vector product. The integral measures the rotation of the maximum principal strain direction and the integration of strain amplitude after the rotation. Therefore; f_{NP} totally evaluates the severity of non-proportional loading in a cycle.

Fig. 5 (a) shows failure life correlated by $\Delta\varepsilon_{NP}$. A relative good correlation can be seen in the LCF region but the failure life in the high cycle fatigue region tends to be underestimated. Fig. 5 (b) is a comparison of the failure life in evaluation N_f^{eva} and experiment N_f^{exp}; where N_f^{eva} is evaluated from the life curve in the push-pull loading test and the following equation

$$\Delta\varepsilon_{eq} = \frac{AN_f^{-0.12} + BN_f^{-0.6}}{1 + \alpha\, f_{NP}} \tag{4}$$

Fig. 5 (b) also shows conservative estimation of failure life in the high cycle fatigue region. In the figure; data which did not reach to failure are omitted. The cause of the underestimation of N_f^{eva} in high cycle fatigue region is considered from that Eq. (4) does not take into account the effect of non-proportional loading on life being weak under elastic deformation. Actually; additional hardening becomes smaller in the lower stress and strain levels. In order to modify non-proportional strain range; the effect of non-proportionality depending on strain level is discussed in next section.



(a) Correlation of N_f with $\Delta\varepsilon_{NP}$

(b) Comparison of N_f^{eva} and N_f^{exp}

Figure 5: Evaluation of failure life by non-proportional strain range.

Modified Non-proportional Strain Range

Fig. 6 shows correlations of N_f with elastic and plastic strain ranges ($\Delta\varepsilon^e_{eq}$ and $\Delta\varepsilon^p_{eq}$). $\Delta\varepsilon^e_{eq}$ in the circle loading test is defined as $\Delta\varepsilon^e_{eq}=AN_f^{-0.12}$ based on elastic part of universal slope curve [16] and $\Delta\varepsilon^p_{eq}$ is defined as $\Delta\varepsilon^p_{eq}=\Delta\varepsilon_{eq} - \Delta\varepsilon^e_{eq}$; where $\Delta\varepsilon_{eq}$ is the strain range obtained by test results. In Fig. 6; the bold lines show the relationships of $\Delta\varepsilon^e_{eq}$–N_f and

$\Delta\varepsilon^{p}_{eq}$–$N_f$; the thin line shows the relationship of $\Delta\varepsilon^{p}_{eq}$–$N_f$ assuming $\Delta\varepsilon^{p}_{eq}$ to be $BN_f^{0.6}/(1+\alpha\, f_{NP})$. The relationships of $\Delta\varepsilon^{p}_{eq}$–$N_f$ are drawn by separate lines in the proportional loading and the non-proportional loading. This results show that the elastic deformation behaviour may be independent on the non-proportional loading becomes of the smaller chance of interaction of slip systems due to non-proportional loading [2;3;6;12]. In order to estimate the effect of non-proportional loading in the lower stress/strain level; the modified equation is presented as

$$\Delta\varepsilon_{eq} = AN_f^{-0.12} + \frac{BN_f^{-0.6}}{1+\alpha\, f_{NP}} \tag{5}$$

Fig. 7 shows comparison between N_f^{eva*} and N_f^{exp}. N_f^{eva*} is evaluated by the modified non-proportional strain range defined in Eq. (5). In Fig. 7; almost of the data are replotted within the factor of 2 band and the correlation becomes better in comparison with that in Fig. 5 (b). Therefore the modified non-proportional strain range becomes a suitable parameter for life evaluation in the high and the low strain levels under non-proportional loading. However; the definition of α still needs more discussion with additional experimental results in future studies.

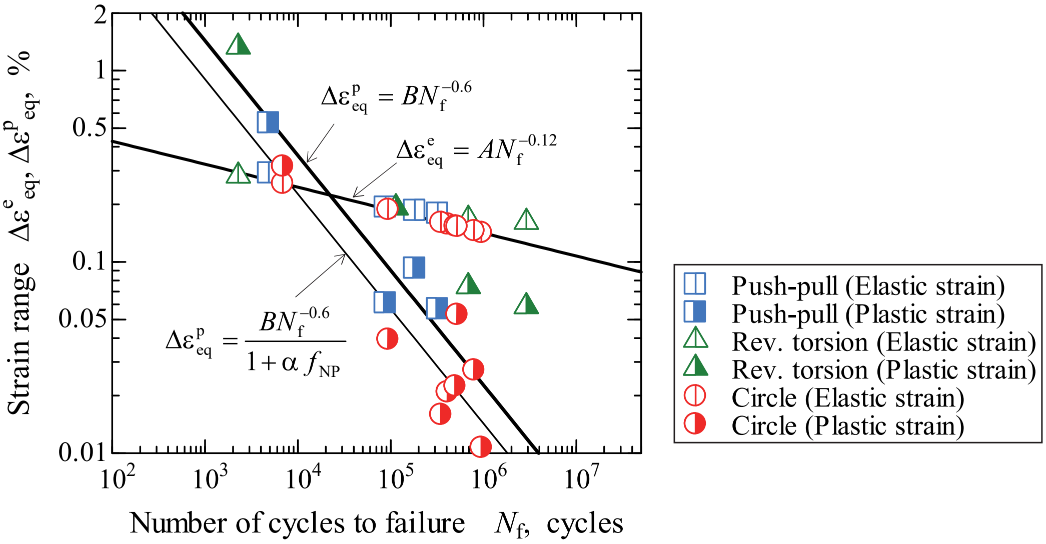


Figure 6: Correlations of N_f by $\Delta\varepsilon^{e}_{eq}$ and $\Delta\varepsilon^{p}_{eq}$.

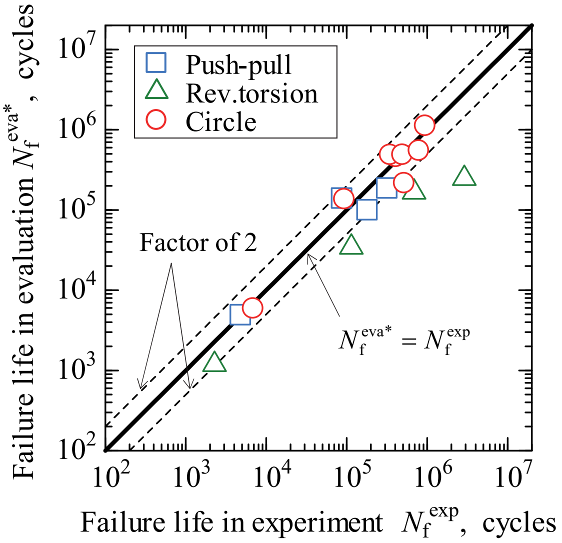


Figure 7: Comparison of N_f^{eva*} and N_f^{exp}.

CONCLUSIONS

(1) The failure life in proportional and non-proportional loading tests can be correlated by a unique life curve in the stress region over the fatigue strength.
(2) The fatigue strength in the circle loading test is lower than that in the push-pull and the rev. torsion loading tests. In the circle loading test; the remarkable roughness can be observed in comparison with those in the push-pull loading test at each equivalent stress range. The surface roughness leads to earlier crack initiations and reducing fatigue strength.
(3) In the circle loading test; non-proportional strain range tends to overestimate failure life in the high cycle fatigue region because the effect of non-proportional loading becomes weak.
(4) The modified non-proportional strain range is the suitable strain parameter for life evaluation independent on strain path and strain level.

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