Theoretical and Applied Fracture Mechanics xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Theoretical and Applied Fracture Mechanics

journal homepage: www.elsevier.com/locate/tafmec

Evaluation of multiaxial low cycle fatigue life for type 316L stainless steel notched specimen under non-proportional loading

Takahiro Morishita [a], Takamoto Itoh [b,*]

[a] Graduate School of Science & Engineering, Ritsumeikan University, Japan
[b] Department of Mechanical Engineering, College of Science & Engineering, Ritsumeikan University, 1-1-1, Noji-higashi, Kusatsu-shi, Shiga 525-8577, Japan

ARTICLE INFO

Article history:
Available online xxxx

Keywords:
Low cycle fatigue
Notch
Life prediction
Combined stress
Non-proportional loading
Finite element analysis

ABSTRACT

This study discusses a multiaxial low cycle fatigue (LCF) life of notched specimen under proportional and non-proportional loading conditions at room temperature. Multiaxial LCF tests controlled by strain were carried out using a smooth and a circumferentially notched round-bar specimens of type 316L stainless steel (316LSS). Four kinds of notched specimens of which elastic stress concentration factors K_t are 1.5, 2.5, 4.2 and 6.0 were employed. The strain paths employed were proportional loading and non-proportional loading. The former is push–pull loading and reversed torsion loading and the latter is circular loading achieved by the strain path of which axial and shear strains are loaded by 90° sinusoidal out-of-phase. Total axial strain and total shear strain ranges were the same ranges based on von Mises. An evaluation of the fatigue life for the notched specimen is discussed based on the experimental results and also by employing an inelastic finite element analysis (FEA). The fatigue life is decreased with increase in K_t at each strain path and is underestimated by a maximum local strain range evaluated by FEA result. A proposed strain range defined by a local mean strain value near the notch calculated from FEA by taking into account the non-proportional effect is an appropriate parameter for life evaluation of 316LSS notched specimen under non-proportional loading.

1. Introduction

Structural components often undergo multiaxial low cycle fatigue (LCF) damage under non-proportional loading in which principal directions of stress and strain are changed in a cycle. Moreover those structural components have various shapes and an excessive stress concentration occurs in some cases. Therefore, it has been required to develop an appropriate design parameter with taking into consideration the non-proportional loading and the stress concentration for reliable design and maintenance of the structural components.

Several researchers have carried out multiaxial LCF tests under non-proportional loading [1–19]. Itoh et al. have already carried out a series of multiaxial LCF tests under non-proportional loading with various strain paths in the combined axial and shear loading by using a hollow cylinder specimen and have examined the dependence of the fatigue life on strain path and material. They have also proposed a strain parameter $\Delta\varepsilon_{NP}$ for evaluation of multiaxial LCF life for smooth specimen under non-proportional loading [11,13,16,19]. Although Berto et al. have proposed a strain energy density (SED) to evaluate the multiaxial LCF life of notched specimen under proportional loading [20–25], few studies in the multiaxial LCF for the notched specimen under non-proportional loading have been reported [26–30] and also an applicability of $\Delta\varepsilon_{NP}$ to the fatigue life evaluation for the notched specimen under non-proportional loading has not been discussed yet.

This study carried out the multiaxial LCF test by using a smooth and a circumferentially notched specimens of type 316L stainless steel (316LSS) under proportional and non-proportional loading. The notch dependency of the fatigue life is discussed based on the experimental results. The fatigue life evaluation is also discussed by analyzing local stress and strain using an inelastic finite element analysis (FEA).

2. Test material and experimental procedure

Material tested was the austenitic stainless steel 316LSS. Specimens used were the smooth solid round-bar specimen and the circumferentially notched solid round-bar specimens of which the elastic stress concentration factors K_t were 1.5, 2.5, 4.2 and 6.0, where the nominal stress is defined in a net cross section. In reversed torsion loading, the elastic stress concentration factors of notched specimens for K_t = 1.5, 2.5, 4.2 and 6.0 are replaced by

* Corresponding author. Tel.: +81 (0)77 561 4965; fax: +81 (0)77 561 2665.
E-mail address: itohtaka@fc.ritsumei.ac.jp (T. Itoh).

http://dx.doi.org/10.1016/j.tafmec.2016.02.007
0167-8442/

Nomenclature

ds	infinitesimal trajectory of loading path
$\boldsymbol{e}_1$	unit vectors for S_{Imax}
$\boldsymbol{e}_{\mathrm{R}}$	unit vectors for $S_{\mathrm{I}}(t)$
F	axial load
f_{NP}	non-proportional factor
K_s	elastic shear stress concentration factor
K_t	elastic stress concentration factor
L_{path}	whole loading path length during a cycle
N_f	number of cycles to failure
r_w	distance from notch root to point at $\varepsilon^F{}_{\mathrm{eq}} = \varepsilon_w$
$S_{\mathrm{I}}(t)$	maximum absolute value of principal strains at time t
S_{Imax}	maximum value of $S_{\mathrm{I}}(t)$
α	material constant
γ	nominal shear strain
$\Delta\varepsilon^F{}_{\mathrm{L}}$	local strain range obtained from FEA
$\Delta\varepsilon^F{}_{\mathrm{NP}}$	local strain range for non-proportional loading obtained from FEA
$\Delta\varepsilon^F{}_{\mathrm{NPmean}}$	local mean strain range for non-proportional loading obtained from FEA
$\Delta\varepsilon_{\mathrm{I}}$	maximum principal strain range
$\Delta\varepsilon_{\mathrm{L}}$	equivalent local total strain range based on von Mises
$\Delta\varepsilon^{\mathrm{L}}_{\mathrm{NP}}$	local strain range for non-proportional loading
$\Delta\sigma$	nominal axial stress range
$\Delta\sigma_L$	equivalent local stress range based on von Mises
$\Delta\tau$	nominal shear stress range
ε	nominal axial strain
$\varepsilon^F{}_{\mathrm{eq}}$	equivalent strain based on von Mises and FEA
$\varepsilon^F{}_{\mathrm{mean}}$	local mean strain range obtained from FEA
$\varepsilon_{\mathrm{I}}(t)$	maximum absolute value of principal strain at time t
$\varepsilon_{\max}$	maximum equivalent strain at notch root
ε_w	strain at fatigue limit

K_s = 1.17, 1.55, 1.87 and 1.96, respectively where K_s is the elastic shear stress concentration factor [31]. Shapes and dimensions of the specimens employed are shown in Fig. 1a–e. No heat treatment was applied to the specimen after machining.

Total strain controlled multiaxial LCF tests were carried out at room temperature under 3 types of strain paths. They are a push–pull, a reversed torsion (rev. torsion) and a circular loading (circle) tests which are shown on $\varepsilon - \gamma/\sqrt{3}$ coordinates in Fig. 2, where ε and γ are a nominal axial and a nominal shear strains. The push–pull test is the axial tension and compression strain test, the rev. torsion test is the cyclic revised pure torsion strain test and the circle test is the circular strain test of which ε and γ have 90° sinusoidal phase difference. The push–pull and the rev. torsion tests correspond to the proportional loading tests and the circle test to non-proportional loading test where the principal directions of stress and strain are rotated in a cycle. The equivalent strain range $\Delta\varepsilon_{\mathrm{eq}}$ employed was 0.7% and a strain rate was 0.1%/s based on von Mises. The gauge length for measuring axial and torsional displacements by an extensometer was 7 mm for all types of specimens. Thus, the extensometer was attached over the notch.

Number of cycles to failure N_f was defined as the cycle at which the stress amplitude was decreased to 3/4 of the maximum value. Axial stress amplitude was employed in the push–pull and the circle tests and shear stress amplitude in the rev. torsion test for judgment of N_f.

3. Experimental results and discussion

3.1. Fatigue life and life evaluation

Table 1 summarizes test results. In the table, $\Delta\sigma$ and $\Delta\tau$ are a nominal axial stress range and a nominal shear stress range at a half cycle of N_f. In the rev. torsion test of K_t = 1.0, the specimen did not reach to the failure over than 100,000 cycles, the test was interrupted at 135,000 cycles. Fig. 3 shows a comparison of N_f in each test at $\Delta\varepsilon_{\mathrm{eq}}$ = 0.7%. In the push–pull test, N_f is decreased with the increase in K_t and N_f at K_t = 6.0 becomes approximately 6% of that at K_t = 1.0. The same trend can be seen in the rev. torsion test. The circle test also shows the similar property but the longest N_f is shown at K_t = 1.5. This may be resulted from a relaxation of the additional hardening at notch part, which will be mentioned later.

Fig. 4 shows a correlation of N_f with a local strain range $\Delta\varepsilon_{\mathrm{L}}$ defined by

$$\Delta\varepsilon_{\mathrm{L}} = \begin{cases} K_t\Delta\varepsilon_{\mathrm{eq}} = K_t\,\Delta\varepsilon & \text{for push—pull and circle tests} \\ K_s\,\Delta\varepsilon_{\mathrm{eq}} = K_s\Delta\gamma/\sqrt{3} & \text{for rev. torsion test} \end{cases} \quad (1)$$

In all the figures correlating N_f in this paper, solid marks denote the results obtained from experiments in this study and open marks the reference data in the authors' previous study using a 316SS smooth specimen [19]. The bold solid line is drawn based on the reference data of the push–pull test and the thin lines show a factor of 2 band. N_f in the push–pull test can be correlated within the factor of 2 band. N_f in the rev. torsion test is also correlated within the band although the data are underestimated in a lower strain level of which stress level is close to the fatigue limit. In the circle test, on the other hand, N_f is overestimated by a factor of 2–3 band and it is almost correlated by a unique line. The reduction in N_f due to non-proportional loading also have been reported in multiaxial LCF studies using the hollow cylinder smooth specimen for various materials [8–10,13–16,19]. Although the scatter of the data correlation in Fig. 4 is shown, $\Delta\varepsilon_{\mathrm{L}}$ can correlate N_f in the push–pull and the rev. torsion tests well and N_f in the circle test, separately. Therefore, $\Delta\varepsilon_{\mathrm{L}}$ has a possibility to become a suitable parameter taking into account the notch effect in proportional and non-proportional loading. However, $\Delta\varepsilon_{\mathrm{L}}$ is not exactly the local strain because $\Delta\varepsilon_{\mathrm{L}}$ is calculated from the nominal strain in the gauge part assuming elastic condition in spite of inelastic condition actually at the notch root.

Fig. 5 shows a correlation of N_f with a local stress range $\Delta\sigma_L$ defined by

$$\Delta\sigma_{\mathrm{L}} = \begin{cases} K_t\,\Delta\sigma & \text{for push—pull and circle tests} \\ K_s\sqrt{3}\Delta\tau & \text{for rev. torsion test} \end{cases} \quad (2)$$

In the push–pull and the circle tests, the data at K_t = 1.0 are plotted within the factor of 2 band. However, the other data are plotted very conservatively and the degree of the conservative estimation becomes remarkable with increasing in $\Delta\sigma_L$ resulting from the increase of K_t. N_f in the rev. torsion test is correlated more conservatively and N_f in the circle test is less conservatively in comparison with N_f in the push–pull test. It is reported that the stress concentration factor is not always constant due to inelastic deformation and decreases with the increase in nominal stress [29,32]. This is the reason for the underestimation of N_f in the higher stress level.

Please cite this article in press as: T. Morishita, T. Itoh, Evaluation of multiaxial low cycle fatigue life for type 316L stainless steel notched specimen under non-proportional loading, Theor. Appl. Fract. Mech. (2016), http://dx.doi.org/10.1016/j.tafmec.2016.02.007