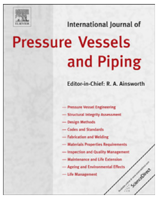
ARTICLE IN PRESS

International Journal of Pressure Vessels and Piping xxx (2016) 1–9

Contents lists available at ScienceDirect

International Journal of Pressure Vessels and Piping

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



Multiaxial fatigue strength of type 316 stainless steel under push–pull, reversed torsion, cyclic inner and outer pressure loading

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ARTICLE INFO

Article history:
Available online xxx

Keywords:
Fatigue
Low cycle fatigue
Multiaxial loading
Non-proportional loading
Life evaluation
Inner and outer pressure

ABSTRACT

Multiaxial fatigue tests under non-proportional loading in which principal directions of stress and strain are changed in a cycle were carried out using a developed multiaxial fatigue testing machine which can load a push–pull and reversed torsion loading with cyclic inner and outer pressure. This paper presents the developed testing machine and experimental results under several multiaxial loading conditions including non-proportional loading. In strain control tests, the failure life is reduced in accordance with increasing inner pressure at each strain path. The failure life can be correlated by von Mises' equivalent stress amplitude relatively well independent of not only inner pressure but also loading path. In load control tests, the failure life is reduced largely by non-proportional loading but the influence of inner and outer pressure on the failure life is relative small.

1. Introduction

Components and structures like pressure vessels and high temperature exchangers undergo multiaxial low cycle fatigue (LCF) damage. In multiaxial LCF under strain controlled non-proportional loading condition in which directions of principal stress and strain are changed in a cycle, it has been reported that fatigue life is reduced accompanying with an additional hardening which depends on both strain path and material [1–10]. Multiaxial LCF usually has been studied using a hollow cylinder specimen by applying axial and twist loads and an applicability of multiaxial stress and strain parameters has been discussed. However, a principal strain ratio (ϕ) range performable by the testing method is $-1 \leq \phi \leq -\nu$, where ν is the Poisson's ratio. Structural components under service loadings sometimes receive LCF damage at principal strain ratio exceeding in the above range. Therefore, fatigue damage evaluation in much wider principal strain ratio range is necessary for a safe design of the high temperature components. Several studies have tried to develop the testing machine that can perform the test in the widely ranged multiaxial states under non-proportional loading [4]. However, no fruitful test result has been obtained because there still exists very high technical hurdles for carrying out the test and developing performable testing machines.

In this study, a multiaxial fatigue testing machine which can apply loads of the push–pull and the reversed torsion and the cyclic inner and outer pressure using the hollow cylinder specimen is presented. The testing machine was developed by applying new ideas and techniques in order to perform fatigue test with widely ranged multiaxial states under non-proportional loading. In addition, multiaxial fatigue tests by the testing machine were carried out using the hollow cylinder specimen of type 316 stainless steel to discuss failure life under the wide ranged multiaxial loading.

2. Types of multiaxial stress and strain states and multiaxial fatigue testing method

This section discusses the definition of uniaxial and multiaxial stress states as well as the definition of proportional and non-proportional loading.

2.1. Uniaxial and multiaxial stress and strain states

A stress state is defined as multiaxial state if the multiple principal stresses operate and a strain state as multiaxial state when the multiple principal strains do. Using these definitions, the multiaxial stress state does not always correspond to the multiaxial

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http://dx.doi.org/10.1016/j.ijpvp.2016.02.024

Please cite this article in press as: T. Morishita, et al., Multiaxial fatigue strength of type 316 stainless steel under push–pull, reversed torsion, cyclic inner and outer pressure loading, International Journal of Pressure Vessels and Piping (2016), http://dx.doi.org/10.1016/j.ijpvp.2016.02.024

strain state. For example, Fig. 1, the uniaxial tension is a uniaxial stress state because only one principal stress operates in tensile direction but this case becomes the multiaxial strain state because the two additional principal strains are caused by the lateral contraction as well as the tensile direction. These definitions of multiaxiality are most consistent for describing the multiaxial stress and strain states compared to using the other stress and strain components, whereas the stress multiaxiality does not always correspond to the strain multiaxiality.

The multiaxial loading is divided into two types in accordance with the direction change of the principal stress and strain. One is proportional loading in which the directions of the principal stress and strain are fixed in a cycle. The other is non-proportional loading in which the direction are changed during cycles.

2.2. *Proportional loading*

Fig. 2 summarizes the applied strains and the strain multiaxiality in various proportional multiaxial testing methods. The discussion in this section is confined to the plane stress condition, because most of the failure of structures initiated from the free-surface in LCF.

In the push–pull (tension-compression) test in the figure, a uniaxial strain (ε) is applied to the specimen but the multiple principal strains arise in the specimen. The lateral strain is $-\nu\varepsilon$ and ν is equated as $-\varepsilon_3/\varepsilon_1$ for $|\varepsilon_1| \geq |\varepsilon_3|$ and $-\varepsilon_1/\varepsilon_3$ for $|\varepsilon_1| \leq |\varepsilon_3|$ in the uniaxial loading test at an in-elastic deformation regime, where ε_1 and ε_3 are the maximum and the minimum principal strain, respectively. The value of ν is usually around 0.3 in an elastic regime but it is 0.5 in a fully plastic regime. In LCF regimes, ν takes the value between 0.3 and 0.5. In the reversed torsion test in the figure, the applied strain is only the shear strain (γ) but the two principal strains with the opposite sign are caused in this case. Therefore the reversed torsion test also becomes a multiaxial test. The tension-compression and reversed torsion and the biaxial tension-compression loading also enable the LCF test in multiaxial strain states. The former test only covers the strain biaxiality for $-1 \leq \phi \leq -\nu$ but the latter test does $-1 \leq \phi \leq +1$.

The similar figure for the applied stress and the stress multiaxiality can be illustrated, but a graphical representation of the figure is not made here to avoid the repetition of the similar figure. In the stress based tests, only the tension-compression loading is a uniaxial test but all the other cases become the multiaxial tests.

2.3. *Non-proportional loading*

Fig. 3 shows the tension-torsion and the biaxial tension-compression tests with phase shift in applied strains. In the tension-torsion test with the phase shift, the direction of the principal strains rotates during testing times and this loading becomes non-proportional loading. The phase shift in applied strain in the biaxial tension-compression test using the cruciform specimen causes no rotation of the principal strain directions but it causes the switch of the principal strain directions. The authors consider that this loading should be classified into proportional loading because no large additional hardening and little reduction in LCF life were confirmed in this type of test using a type 304 steel cruciform specimen at 823 K [11]. Another researches [12–14], however, stated that this loading should be a type of non-proportional test showing a fair reduction in fatigue life in experiments. More detailed experimental studies and evidences are needed to have a definite conclusion on the classification of this type of loading.

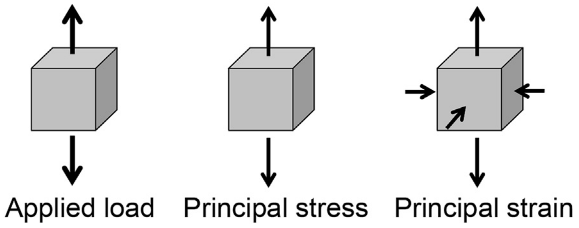

Fig. 1. Principal stress and principal strain in tension loading.

Itoh et al. [10] presented a quantitatively definition of the degree of non-proportionality of loading (f_{NP}; non-proportional factor) defined by,

$$f_{NP} = \frac{\pi}{2\, S_{\mathrm{Imax}} L_{\mathrm{path}}} \int_C |\boldsymbol{e}_1 \times \boldsymbol{e}_R| S_{\mathrm{I}}(t) \mathrm{d}s, \quad L_{\mathrm{path}} = \int_C \mathrm{d}s \tag{1}$$

where $S_{\mathrm{I}}(t)$ is a maximum value of principal stress or principal strains. $\boldsymbol{e}_{\mathrm{R}}$ is a unit vector directing to $S_{\mathrm{I}}(t)$, ds the infinitesimal trajectory of the loading path. L_{path} is the whole loading path length during a cycle and "×" denotes vector product. The scalars, S_{Imax} and L_{path}, before the integration in Eq. (1) is set to make f_{NP} unity in the circler loading in 3 dimensional polar figure. Integrating the product of amplitude and principal direction change of stress and strain by path length in Eq. (1) is suitable parameter for evaluation of the additional damage due to non-proportional loading. Detail descriptions of f_{NP} and life evaluations are mentioned in Refs. [9,10].

2.4. *Definition of multiaxial stress and strain state*

Multiaxial stress and strain state can be expressed by using parameters, κ and φ, as defined by Eq. (2) and Eq. (3),

$$\kappa = \frac{\tau}{\sigma} \tag{2}$$

$$\varphi = \frac{\gamma}{\varepsilon} \tag{3}$$

where κ and φ are a stress and a strain ratios, respectively.

Besides the method above, this paper also employs a principal stress ratio, λ, and the principal strain ratio, ϕ, to defined multiaxial stress and strain states, which are equated by Eq. (4) and Eq. (5).

$$\lambda = \frac{\sigma_{\mathrm{II}}}{\sigma_{\mathrm{I}}} \tag{4}$$

$$\varphi = \frac{\varepsilon_{\mathrm{II}}}{\varepsilon_{\mathrm{I}}} \tag{5}$$

where σ_{I} and σ_{II} are put as σ_1, σ_2 or σ_3 of which absolute values take the largest and middle ones, *e.g.* if $\sigma_1 = 100$ MPa, $\sigma_2 = 50$ MPa and $\sigma_3 = -200$ MP, $\sigma_{\mathrm{I}} = -200$ MPa and $\sigma_{\mathrm{II}} = 100$ MPa since $|\sigma_3| \geq |\sigma_1| \geq |\sigma_2|$. On the other hand, ε_{I} and $\varepsilon_{\mathrm{II}}$ are principal strains of which principal directions correspond to those of σ_{I} and σ_{II}, respectively. In the proportional fatigue test, λ and ϕ have constant values in a cycle.

2.5. *Fatigue testing method*

In order to obtain the fatigue data under multiaxial loading for different materials, various kinds of multiaxial fatigue tests is carried out. Fig. 4 shows four types of most representative testing methods classified by loading and shapes of specimens. Type IA is the tension-compression and reversed torsion test using the hollow

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