

Study on the creep and fatigue interaction of a Nimonic Alloy 75 under multiaxial nonproportional loading

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Abstract. In this paper, a unified viscoplastic model was utilised to numerically simulate cyclic hardening of a nimonic alloy 75 under multiaxial non-proportional cyclic straining at elevated temperature. Description of the constitutive model and interpretation of material parameter were also presented. Constitutive simulations for the circular and square cycling strain paths in the axial-torsional plane have been verified by the test results, and the possibility of this model extension was also discussed.

Introduction

Understanding multiaxial cyclic deformation behaviors is important in inelastic structural analysis including fatigue assessment of structural components in the industry since structural components are subject to complex stressings or strainings in practical [1]. Nonproportional cyclic loading causes more damage than proportional loading and occasionally reduces low cycle fatigue. During the analysis of components subject to multiaxial load, the problem often goes to an “equivalent” uniaxial fatigue case without thought as to whether the simplifying assumptions are valid for the specific load sequence or component being considered. Although in recent years, amount of research work on this area have been published, however, for this non-expert field, these works often are difficult to digest and complex to apply [2].

Over last several decades, a number of constitutive models describing inelastic deformation for the multiaxial loading at elevated temperature have been proposed [3-9]. But less published researches on the creep and fatigue problem under multiaxial non-proportional strain and stress cycling loading are conducted. So development of more general and proper constitutive models may be a root to solve above problems and difficulties of the multiaxial fatigue. This kind of constitutive models can be used to simulate more general and complex loading by the incremental plasticity and viscoplasticity procedures, and also can be finally implemented into the structure analysis and design software like ABAQUS and ANSYS et al. for industry practice purpose.

This paper presents a primarily modelling of the creep and fatigue interaction under multiaxial strain loading. The plasticity and viscoplasticity constitutive model include non-linear kinematic hardening rule was proposed by Chaboche [9]. The main work focus upon the constitutive simulation of a nimonic alloy 75 under multiaxial non-proportional cyclic straining conditions for verifying the model application.

Experimental description

The experimental results were obtained in a Nimonic Alloy 75. An MTS809 servo-hydraulic testing machine was used with the computer controlled loading spectra programmed as required. An electric resistance furnace was used with the temperature controlled at $620\pm 5^{\circ}\text{C}$. An extensometer

(25+2.5/-2.5mm) was used to monitor the strain. All tests were carried out under strain control at a constant strain rate 0.2%/s

Smooth specimens with a diameter of 16 mm and gauge length of 30 mm were used for the uniaxial experiments and parameters estimated. A baseline cyclic test and a multiple-step cyclic test were carried out to obtain the full cyclic stress-strain. A strain ratio $R_\epsilon=-1$ and the strain range of 2% were used for the baseline test while strain ranges of 1.2, 1.6 and 2% were used for the multiple-step test at $R_\epsilon=-1$. Multiple hardening and relaxation test were carried out where the strain was held constant at selected levels (1.0% - 2.2%) for 100-300 seconds. The stress relaxation was recorded during the tests.

Specimens employed for multiaxial experiments were thin-walled tube with the outside diameter, wall thickness and gage length of 15 ± 0.05 , 3 ± 0.05 and 100 mm, respectively. And the axial strain range $\Delta\epsilon/2$ and torsional strain range $\Delta(\gamma/3^{1/2}/2)$ are 0.8%. The strain cycling path includes circular and square strain loading for the multiaxial nonproportional cyclic hardening were used here for the constitutive simulation purpose. The effective stress $|\dot{s}|$ is denoted as the effective stress amplitude (with $\Delta s / 2$ the axial stress range and torsional stress range):

$$\Delta s_M / 2 = \left[(\Delta s / 2)^2 + (\Delta(\sqrt{3}t) / 2)^2 \right]^{1/2} \quad (1)$$

Chaboche Constitutive Equations

The multiaxial constitutive equations utilized here are based on Chaboche model [9], which is listed at Appendix I. In this formulation the material parameters of the model $Z, n, C_1, C_2, C_3, a_1, a_2, a_3, b, Q, k, b_1, \Phi_\infty$ are all temperature-dependent. The kinematic hardening parameters a_1, a_2, a_3 and C_1, C_2, C_3 , isotropic hardening parameters Q, b and kinematic recovery parameters b_1 and Φ_∞ , the viscoplasticity parameters of time-dependent n, Z, k . The method of determining these parameters based on the uniaxial experimental data, has been discribed in previous work [10, 11 and 12]. The values of material parameter in the constitutive model are listed in Table 1.

Table 1. Materials parameters estimated

Material parameters	Values of parameters
E(MPa)	145
G(MPa)	55
b	7.8
Q (MPa)	136
a_1 (MPa)	121
C_1	632
a_2 (MPa)	85
C_2	459
a_3 (MPa)	36
C_3	287
Z (MPa $s^{1/n}$)	371
n	17
K (MPa)	110
Φ_∞	0.78

Simulation and Discussion

The constitutive simulation program [13, 14, and 15] of multiaxial nonproportional loading (strain controlled) were modified on the present model. Comparisons of experimental and simulated results of the effective stress amplitudes for two nonproportional strain cycling path are shown in the Fig.1. Fig.1 (a) presents experimental and simulated results of effective stress responses of a circular strain path for

number of cycles $N=1-50$ with constant effective strain amplitude 0.8% and a constant strain rate 0.2%/s. Fig.1 (b) presents experimental and simulated results of effective stress responses of a square strain path for number of cycles $N=1-50$ with constant effective strain amplitude 0.8% and a constant strain rate 0.2%/s.

In Fig.1, the experimental results present the rapid reduction of stress amplitude width for describing the cyclic hardening behaviour. The cyclic stabilization followed by, can also be seen during initial few cycles ($N=1-10$) in the Fig.1. Good simulation on the effective stress responses can be observed under both of circular and square paths in Fig.1 (a) and (b), although some over-estimates exist especially for the square strain path. The simulation results are still encouraging; the capability of the present constitutive model is verified by comparisons between simulation and experimental results.

According to the above comparisons, one reason of over-estimate may be caused by the material parameter estimates; the optimisation procedure of material parameters is not carried out in this paper, another one may be that the additional hardening of non-proportional loading may need to be considered in the modelling. In generally, the effect of creep on cyclic plastic behaviours comes to be impairment, especially, at the high temperature. Under the square stress path with the trapezoidal strain cycles, the axial stress and torsional stress holding alternate, the creep and fatigue interaction may be an influence on the experimental results. So the present model without considering creep and fatigue interaction effect may cause the more over-estimate simulation of experimental result than simulation of the circular stress path. Hence, more effects of creep and fatigue interaction on the constitutive model should be incorporated into further studies.

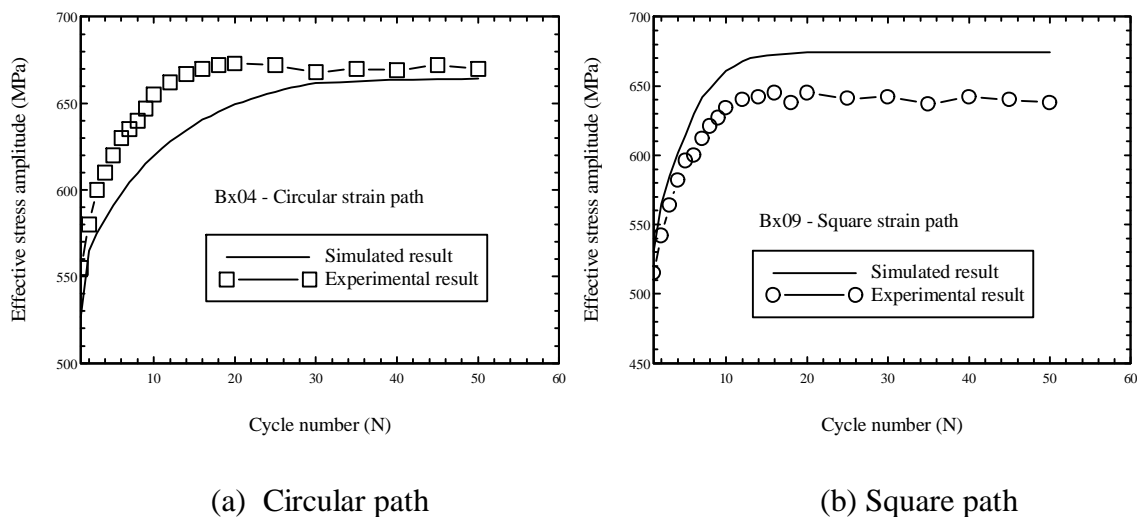


Fig.1 Comparison of experimental result and simulated result of the effective stress amplitudes for two strain control path.

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Appendix I: The Chaboche unified model adopted in this work

Yield Surface $f = J(\hat{s} - \hat{c}) - R - k \leq 0$

$$J(\hat{s} - \hat{c}) = \sqrt{3/2}(\hat{s}' - \hat{c}') : (\hat{s}' - \hat{c}') = \sqrt{3/2}\|\hat{s}' - \hat{c}'\| \quad (A1)$$

Kinematic Hardening $\hat{c} = \sum_{i=1}^m \hat{c}_i$

$$\dot{\hat{c}}_i = C_i(a_i \dot{\hat{e}}_p - \hat{c}_i \Phi_i) \quad i=1-3 \quad (A2)$$

$$\Phi = \Phi_\infty + (1 - \Phi_\infty)e^{-b_1 P}$$

Isotropic Hardening $\dot{R} = b(Q - R)\dot{\hat{e}}_p \quad (A3)$

Flow Rule $\dot{\hat{e}}_p = \frac{3}{2} \left\langle \frac{J(\hat{s} - \hat{c}) - R - k}{Z} \right\rangle^n \frac{\hat{s}' - \hat{c}'}{J(\hat{s} - \hat{c})} \quad (A4)$

$$\langle x \rangle = xH(x) \quad H(x) = \begin{cases} 1, & x \geq 0 \\ 0, & x < 0 \end{cases}$$

Accumulated Plastic Strain $\hat{e}_p = \sqrt{(2/3)\dot{\hat{e}}_p : \dot{\hat{e}}_p} \quad (A5)$

Parameters to be identified: $Z, n, C_1, C_2, C_3, a_1, a_2, a_3, b, Q, k, b_1, \Phi_\infty$