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MULTIAXIAL RATCHETING OF 1CR18NI9TI STAINLESS STEEL

Xu Chen
School of Chemical Engineering & Technology, Tianjin University, Tianjin 300072, P. R. China
Phone: 22-27408399, Fax:22-87893037
E-mail: xchen@eyou.com

Xin Li
School of Chemical Engineering & Technology, Tianjin University, Tianjin 300072, P. R. China
Phone: 86-22-27408399
E-mail: hbsydlut@eyou.com

Rong Jiao
A School of Chemical Engineering & Technology, Tianjin University, Tianjin 300072, P. R. China
Phone: 22-27408399, Fax:22-87893037
E-mail: rongjiao@eyou.com

ABSTRACT

A modified kinematic hardening rule is proposed in which one biaxial loading dependent parameter δ' connecting the radial evanescence term ($(\boldsymbol{\alpha} : \boldsymbol{n})\boldsymbol{n}dp$) in the Burlet -Cailletaud model with the dynamic recovery term of Ohno-Wang kinematic hardening rule is introduced into the framework of the Ohno-Wang model. Compared with multiaxial ratcheting experimental data obtained on 1Cr18Ni9Ti stainless steel, simulation results by modified model are quite well in all loading paths. The simulations of initial nonlinear part in ratcheting curves can be improved greatly while the evolutional parameter δ' related to plastic strain accumulation is added into the modified model.

Keywords: multiaxial loading, ratcheting, cyclic plasticity, kinematic hardening.

1. INTRODUCTION

Several kinematic hardening rules have been proposed for predicting of ratcheting under multiaxial loading. The nonlinear kinematic hardening rule by Armstrong and Frederick (1966) was found to over-predict ratcheting strain significantly under multiaxial loading paths. In these coupled models based on the Armstrong and Frederick nonlinear kinematic hardening rule, the plastic modulus (H_p) is calculated according to the kinematic hardening rule and the consistency condition. Usually the parameters are calculated from the hysteresis loops and uniaxial loading responses. These parameters are, in effect, calibrated to produce a better representation of the hysteresis loop and uniaxial ratcheting, however they fail to predict multiaxial ratcheting responses. In order to solve the problem of over-prediction by the existing models on multiaxial ratcheting responses, many researchers (McDowell, 1995; Jiang and Sehitoglu, 1996) have attempted to add multiaxial terms and parameters into the Chaboche or Ohno-Wang model. However, these modified models do not improve the simulation of the biaxial ratcheting responses compared with the Ohno-Wang model (Bari and Hassan, 2002). Thus Bari and Hassan proposed a modified kinematic hardening rule based on the idea of Delobelle et al (1995) in the framework of the Chaboche (1994) model. Since the Ohno-Wang model is regarded as the best model to predict ratcheting by the researchers (Igaria et al, 2002), it is reasonable to do some modification in the framework of the

Ohno-Wang model. The authors have made an efforts on the modification of Ohno-Wang model(Chen et al, 2004, 2004). This study proposes an improved kinematic hardening rule by introducing one multiaxial parameter δ' to the Ohno-Wang model aiming at investigating the modified model for its validity and applicability of predicting ratcheting under several different multiaxial loading paths.

2. RATCHETING EXPERIMENTS

The material used in the study was 1Cr18Ni9Ti stainless steel in the form of round bar with a diameter of 32mm after being oil-quenched at 1100°C for 30 minutes. The chemical composition of the material is (%wt): C 0.065, Mn 1.34, Si 0.95, P 0.03, S 0.007, Ni 8.74, Cr 17.54, Ti 0.41.

Table 1List of ratcheting experiments

Spec. No.	Path	$\Delta\gamma / 2\sqrt{3}$ (%)	γ_{mean} (%)	$\Delta\sigma$ (MPa)	σ_{mean} (MPa)
M130	Case 1	0.4	0	0	200
M140	Case2	0.4	0	200	200
M150	Case 2	0.6	0	200	200

The specimen used in this study has a tubular geometry with outside and inside diameters of 22mm and 18mm respectively in the gage section. The tests were conducted on an Instron tension-torsion machine with an axial-torsional extensometer mounted on the outside of the specimen gage section. Strain and stress was recorded in the personal computer using an automated data acquisition system. All tests were conducted at room temperature under stress control for axial loading and under strain control for torsional loading. The frequency of cyclic loading was 0.5Hz.

The loading paths in the axial stress-shear strain plane (plane) used in ratcheting tests are illustrated schematically in Fig.1. The controlled parameters are given in Table 1. These tests consist of a constant-amplitude shear strain cycling under a constant axial stress (case 1) and a circular axial stress-shear strain cyclic loading with mean axial stress (case 2).

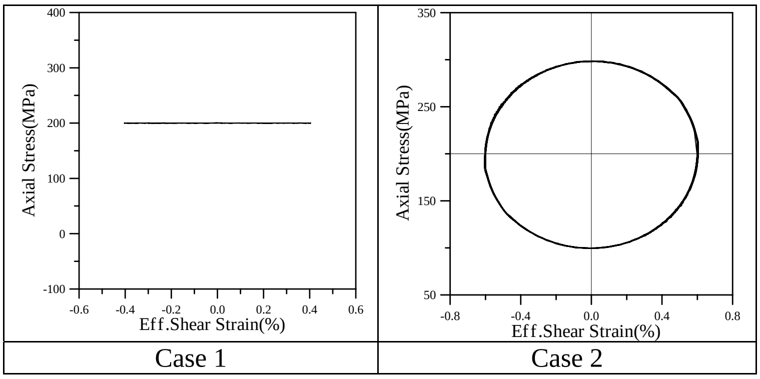


Fig.1 Loading paths in ratcheting experiments

For 1Cr18Ni9Ti stainless steel, the ratcheting experiments reveal that the rate of ratcheting continuously decreases as cycling continues, but does not fully shakedown or cease. The observations of the uniaxial cyclic stress-strain curve for first 16 cycles reveal that very slight cyclic hardening. In the present study, therefore, we neglect the cyclic hardening for simplicity.

Generally speaking, non-proportional additional hardening of materials has some effects on ratcheting and the effects have been taken into account in constitutive models (McDowell, 1995; Jiang and Sehitoglu, 1996a, 1996b). 1Cr18Ni9Ti stainless steel presents significant non-proportional additional hardening under controlled circular strain path (Chen et al, 2004). However, the non-proportional additional hardening of 1Cr18Ni9Ti stainless steel is not obvious in the experiments of the paper because of axial stress is quite low under axial stress-shear strain cyclic loading.

3. MODIFIED CONSTITUTIVE MODEL

In order to simulate the uniaxial ratcheting experiments, Burlet and Cailletaud (1986) modified the radial evanescence term in the Armstrong and Frederick (1966) hardening rule as follows:

$$d\boldsymbol{\alpha} = \frac{2}{3} C d\varepsilon_p - \gamma(\boldsymbol{\alpha} : \boldsymbol{n})\boldsymbol{n} dp, \quad \mathbf{n} = \frac{\partial f}{\partial \boldsymbol{\sigma}} \Big/ \left\| \frac{\partial f}{\partial \boldsymbol{\sigma}} \right\| = \sqrt{\frac{3}{2}} \frac{(\mathbf{s} - \boldsymbol{\alpha})}{\boldsymbol{\sigma_0}} \tag{1}$$

The plastic modulus expression obtained from this hardening rule by satisfying the consistency condition ($\dot{f} = 0$) is the same as that obtained from the Armstrong and Frederick hardening rule. And under uniaxial loading conditions, the direction of $\boldsymbol{\alpha}$ is the same as that of $\boldsymbol{n}$ and hence the radial evanescence term ($(\boldsymbol{\alpha} : \boldsymbol{n})\boldsymbol{n} dp$) is reduced to the dynamic recovery term of Armstrong and Frederick. In addition, because simulations of uniaxial ratcheting responses depend entirely on the calculation scheme of the plastic modulus of a model, these two rules produce the same simulation; while for biaxial loading, the radial evanescence term ($(\boldsymbol{\alpha} : \boldsymbol{n})\boldsymbol{n} dp$) of the Burlet and Cailletaud rule essentially yields a tensor along the plastic strain-rate direction and the simulation of biaxial ratcheting is like the result of Prager linear hardening rule that predicts shakedown ratcheting (Bari and Hassan, 2002). Between over-prediction ratcheting by the Ohno-Wang model and shakedown ratcheting of the Burlet and Cailletaud model, a modified hardening rule incorporating the ideas of both the Burlet-Cailletaud and the Ohno-Wang models with a parameter δ' is proposed as follows:

$$d\boldsymbol{\alpha}_i = \gamma_i \left\{ \frac{2}{3} r_i d\varepsilon_p - \left(\frac{\overline{a_i}}{r_i}\right)^{m_i} \left[\delta' \boldsymbol{\alpha}_i + (1 - \delta')(\boldsymbol{\alpha}_i : \boldsymbol{n})\boldsymbol{n} \right] \left\langle d\varepsilon_p : \frac{\boldsymbol{\alpha}_i}{\overline{\overline{\alpha_i}}} \right\rangle \right\}, i = 1,2,...M \tag{2}$$

where, γ_i, r_i, m_i and $\overline{\alpha_i}$ in Eq. (9) is the same as the Ohno-Wang model. When $\delta' = 0$, the modified hardening rule is reduced to the Burlet-Cailletaud model that predicts the shakedown ratcheting; while if $\delta' = 1$, it reverts to the Ohno-Wang model (II) that over-predicts ratcheting under multiaxial loading conditions.

Following the consistency condition ($\dot{f} = 0$), the plastic modulus is expressed as follows:

$$H_p = \sum_{i=1}^{M} \gamma_i \left\{ r_i - \frac{3}{2} \left(\frac{\overline{a_i}}{r_i}\right)^{m_i} (\boldsymbol{\alpha}_i : \boldsymbol{n}) \left\langle \frac{\boldsymbol{a}_i}{\overline{\overline{a_i}}} : \boldsymbol{n} \right\rangle \right\} \tag{3}$$

In Eq. (3), it can be seen that the plastic modulus expression (H_p) does not include δ' and δ' can be determined by a biaxial ratcheting response, so δ' can influence biaxial ratcheting simulations without having any effect on both the calculation of plastic modulus and the simulations of uniaxial ratcheting responses.

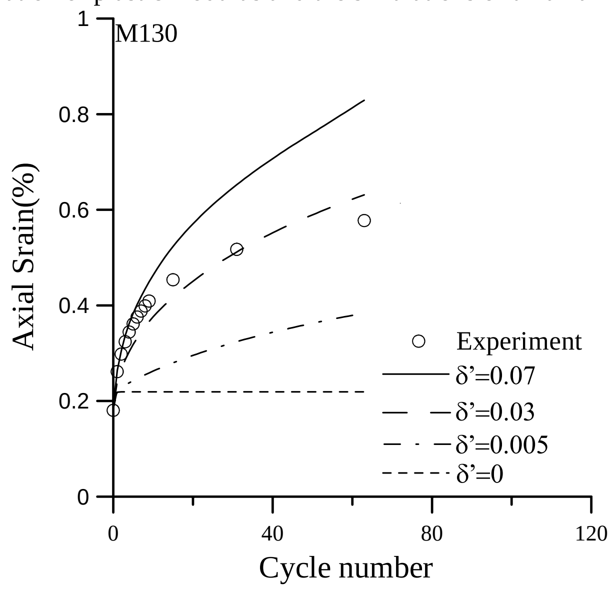


Fig.2 Comparison of experimental ratcheting and predicted ratcheting with constant δ'

Because the plastic modulus expression (H_p) is independent of δ' and is the same as that obtained from the Ohno-Wang model, all of the parameters of the Ohno-Wang model can be used by the modified hardening rule as presented in Table 2. The comparison shows that the stress-stain simulations by two models have no differences. The simulations by the modified model with different δ' are presented in Fig.2 in which we can see that if a larger δ' is assumed, the modified model can simulate the initial nonlinear part but cannot provide the subsequent ratcheting rate trend well, while if a smaller δ' is assumed, the modified model can predict the ratcheting rate trend well but cannot simulate the initial nonlinear part of ratcheting curve. So we can come to the conclusion that the modified model with a constant δ' cannot predict a good simulation of the whole ratcheting curve. Hence it is better to give δ' an evolutionary character to improve the simulation.

Table 2 Model parameters for 1Cr18Ni9Ti stainless steel

σ_0 (MPa)	E (MPa)	m_i $(i = 1 \sim M)$	δ'_o	δ'_{st}	β
235	193000	10	0.07	0.005	8
$\gamma_{1-8} = 4800,2400,1200,600,300,150,75,37.5$					
$r_{1-8} = 10,65,63,41,80,70,16,2\text{MPa}$					

An evolutionary equation for δ' is proposed as follows:

$$d\delta' = \beta(\delta'_{st} - \delta')dp \qquad (11)$$

where, δ'_{st} is the saturated value of δ' and β is an evolutionary coefficient. The initial value of δ' is denoted by δ'_o. The computation for different δ'_{st} (δ'_o and β are kept constant) shows that the value of δ'_{st} allows adjustment of the slope of ratcheting rate trend. The computation for different δ'_o (δ'_{st} and β are kept constant) reveals that δ'_o is closely related to the ratcheting rate of the first several cycles and β decides the ratcheting evolutive rate. The value of δ'_{st}, δ'_o, β and other parameters in the modified model for 1Cr18Ni9Ti stainless steel are given in Table 2.

In this paper, the simulation results by the modified model with constant δ' and evolving δ' are shown by the curves of modified model-1 and the curves of modified model-2 respectively.

Comparisons of improved ratcheting simulations of M130, M140 and M150 by the modified model with evolving parameter δ' and other parameters of the Ohno-Wang model (II) with experimental data are presented in Fig.3-Fig.6.

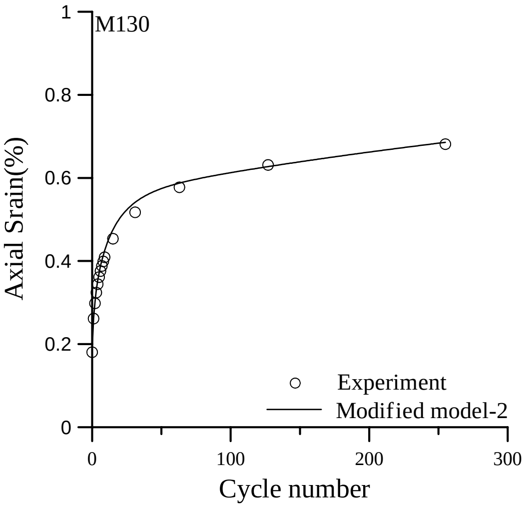


Fig.3 Comparison of experimental ratcheting and predicted ratcheting by the modified model with an evolutional δ' for M130

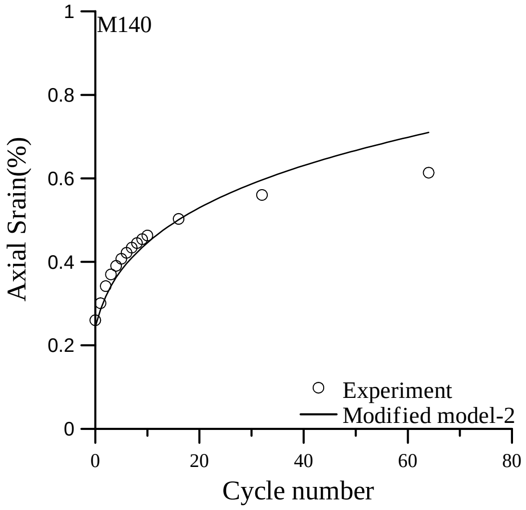
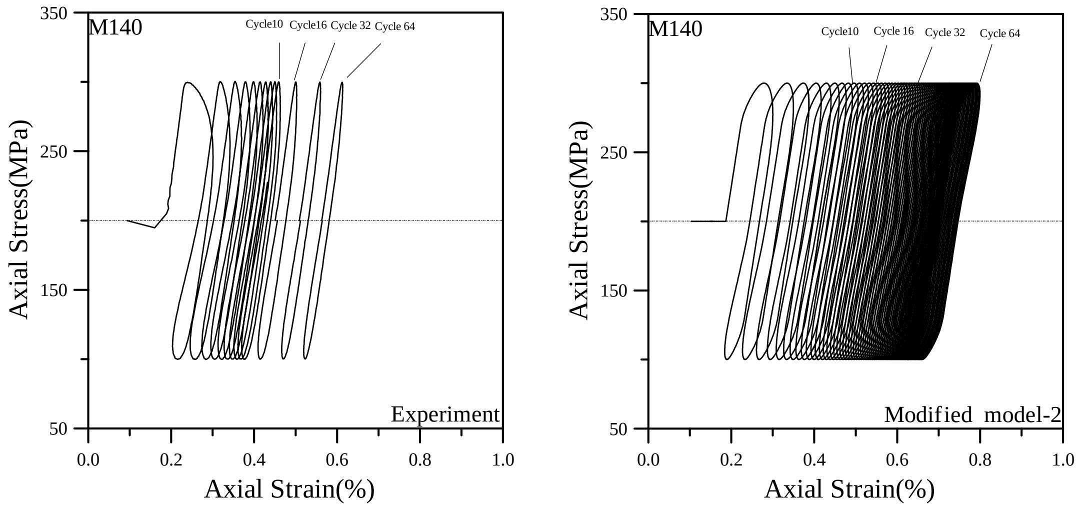
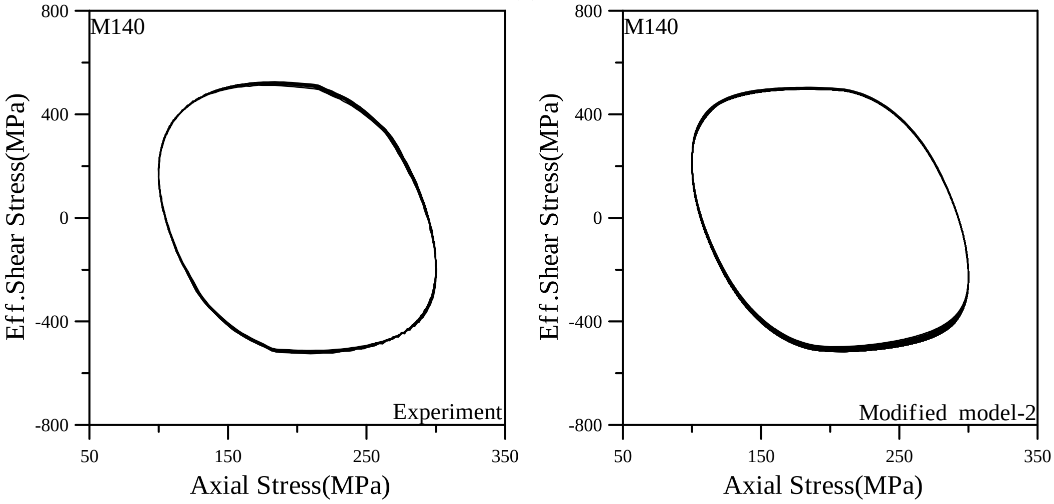


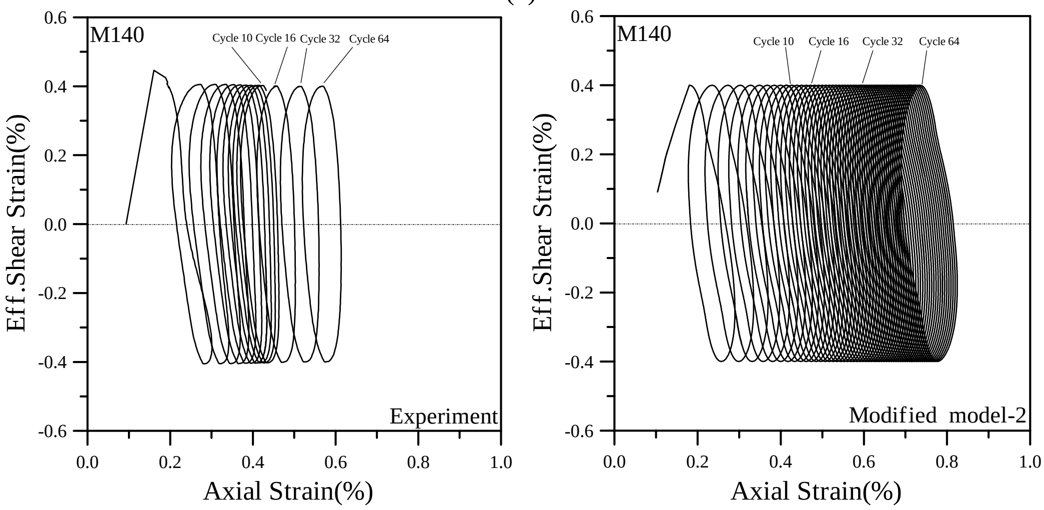
Fig.4 Comparison of experimental and predicted ratcheting for M140



(a)

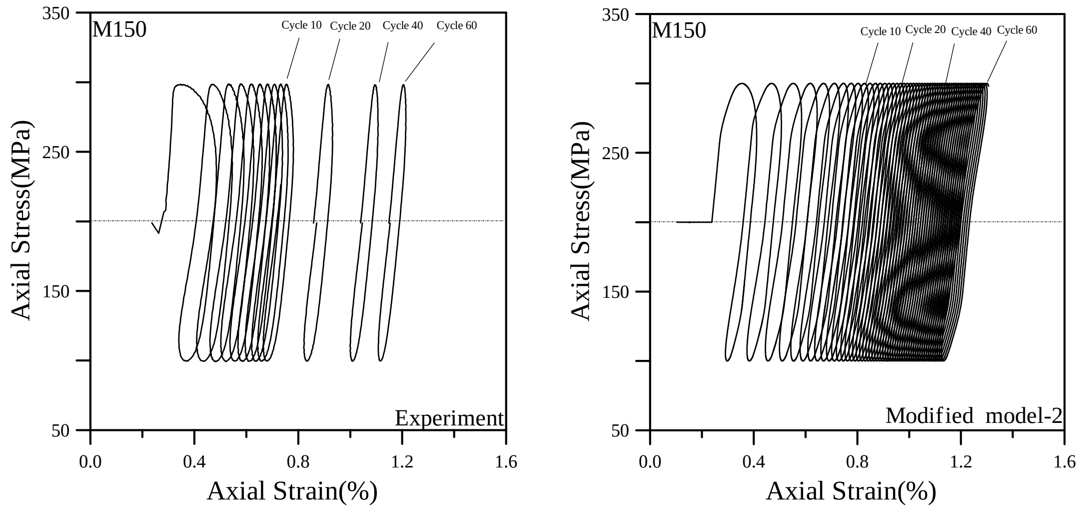


(b)

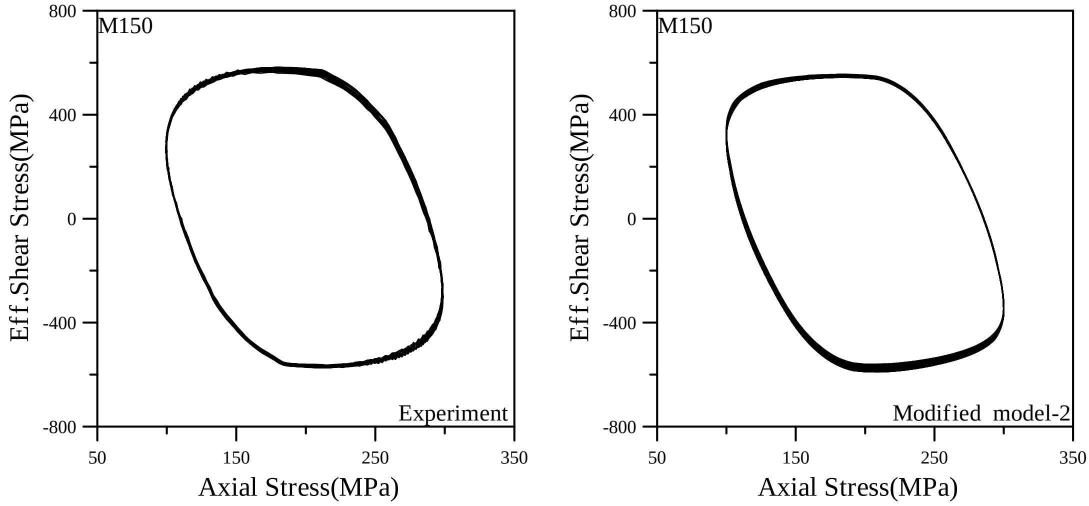


(c)

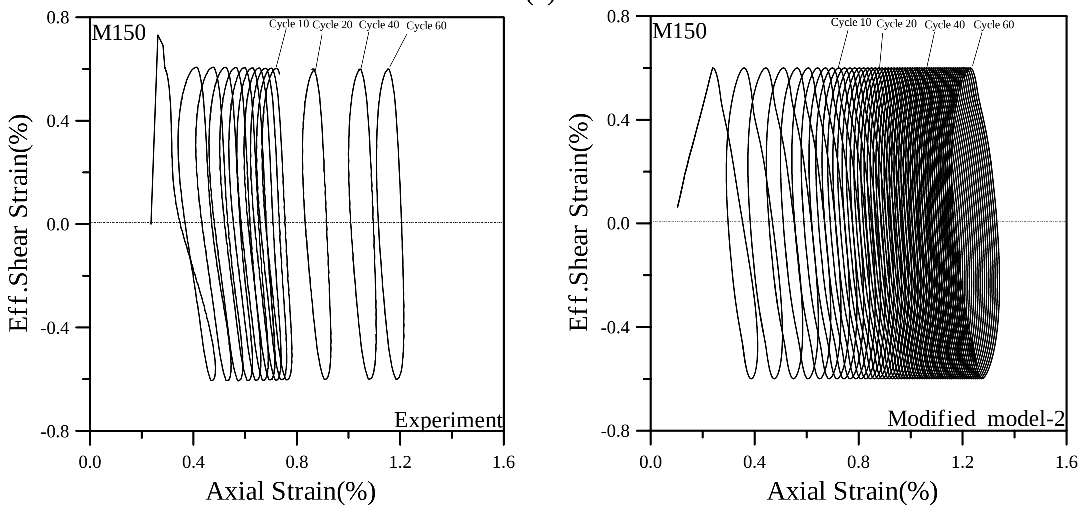
Fig.5 Comparison of experiments and predictions for M140;
(a) axial stress-strain response,(b) stress resHponse, (c) strain response



(a)



(b)



(c)

Fig.6 Comparison of experiments and predictions for M150;
(a) axial stress-strain response,(b) stress response, (c) strain response

It can be seen that the modified model not only predicts the axial ratcheting strain and the stable stress-strain hysteresis loop with reasonable accuracy, and it also simulates the stress response, the strain response and axial stress-strain response well to some degree.

4. CONCLUSIONS

Ratcheting tests were conducted on 1Cr18Ni9Ti stainless steel for two nonproportional loading paths. A modified kinematic hardening rule that incorporates the radial evanescence term ($(\boldsymbol{\alpha} : \boldsymbol{n})\boldsymbol{n}dp$) of the Burlet-Cailletaud model with the Ohno-Wang kinematic hardening rule is proposed. All parameters except a new parameter $\delta^{'}$ of the modified rule are the same as those of the Ohno-Wang models and $\delta^{'}$ can be determined with a biaxial ratcheting response. The parameter determination scheme for this modified model is simple and systematic. In order to improve the simulation to all parts of the ratcheting curves, an evolving parameter $\delta^{'}$ is introduced into the modified model. The model predicts stable stress-strain behavior of the test material with reasonable accuracy. Ratcheting simulations of both two types of loading paths are reasonably accurate for experimental data at low numbers of cycles.

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