Low Cycle Fatigue of Mod.9Cr-1Mo Steel under Multiaxial Loading at High Temperature

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ABSTRACT. *A series of tests for low cycle fatigue are conducted for Mod.9Cr-1Mo ferrite steel under multiaxial loading at 550℃. The effect of strain multiaxiality on the fatigue life under proportional loading is considered by defining the principal strain ratio. The cyclic properties under different strain paths and strain amplitudes for this material are discussed. It is shown that the softening property is observed at high temperature for all the strain paths. The effect of loading path on the softening property is more prominent than that of strain amplitude. The fatigue life is predicted by equivalent strain approach, energy approach, and critical plane approach. It can be concluded that the results for equivalent strain approach are too conservative, the results for energy method, i.e. LKN, are excellent. The prediction lives of SWT approach are nonconservative for the torsion path, but on the whole the prediction lives are acceptable. The prediction results for FS and KBM approach are satisfying and the prediction results for CXH approach are better than that of SWT.*

1 INTRODUCTION

In order to increase the thermal efficiency as well as to reduce the environmental pollution from power generating plants, it is necessary to employ higher steam temperature and pressure than those currently employed. So it is important to develop and apply the materials with improved high temperature properties. It is desirable to use high Cr ferrite steels because of their better resistance to stress-corrosion cracking, higher thermal conductivity, lower thermal expansion coefficient, and lower cost as compared with austenitic stainless steels. Among the high Cr ferritic steels (9-12% Cr), Mod.9Cr-1Mo steel has been chosen as the candidate material for the structural material of steam generator and also receiving the greatest attention from researchers and fabricators worldwide today [1].

Some previous studies for Mod.9Cr-1Mo steel focused on these production technology, welded joints, engineering applications, etc [2,3]. Other research for this material has been done, such as constitutive relationship and the creep property research. Yaguchi[4] proposed a new constitutive model by considering the cyclic softening behavior depending on the temperature and its history based on the test results for Mod.9Cr-1Mo steel at various temperatures, including those under anisothermal conditions. Later, some uniaxial and multiaxial ratcheting tests were conducted at temperatures between 200℃ and 600℃ on Mod.9Cr-1Mo steel by Yaguchi[5]. This material exhibited both viscoplastic and cyclic softening behavior and some anomalous behaviors were observed in the stress-controlled uniaxial ratcheting tests. The material exhibited outstanding ratcheting in the tensile direction under zero mean stress. Koo et al[6] simulated the ratcheting behaviour at high temperatures for Mod.9Cr-1Mo steel by the inelastic constitutive equation of the Chaboche model. A finite element model was employed to calculate the transient temperature and the residual stresses. The hysteresis energy failure density obtained by the numerical simulation was used to describe the fatigue damage for Mod.9Cr-1Mo steel by Joseph et al[7]. A good correlation with experimental results was obtained for life predictions using hysteresis energy density as a damage parameter.

Although many research has been done for Mod.9Cr-Mo steel, on the whole there are fewer results for the fatigue life prediction for this material, especially at high temperature [8]. Low cycle fatigue behavior of Mod.9Cr-1Mo steel under normalized and tempered conditions was reported by Nagesha[9]. It was shown that the cyclic stress response behavior, in general, showed an initial brief hardening for the first few cycles, followed by a continuous and gradual softening regime that ended in a stress plateau that continued up to the specimen failure. The fatigue life decreased as the temperature increased. The effect of temperature on life was more pronounced at low strain amplitudes.

In this paper, a series of uniaxial and multiaxial tests are conducted for Mod.9Cr-1Mo at 550□ due to the material used below 600□ in practice. The principal strain ration ϕ is defined in order to express the effect of strain multiaxiality on the fatigue life for proportional loading. The fatigue life is predicted using Mises equivalent strain approach, energy approach, and critical plane approach. The critical plane approaches are consisted of SWT, FS, KBM, and CXH. The prediction results for different approaches have been discussed.

2 EXPERIMENTS

The chemical composition of Mod.9Cr-1Mo steel used in this investigation is shown in Tab. 1. The detail description for the specimen is shown in Fig. 1. The properties for this material at 550℃are yield stress $\sigma_y = 348MPa$, Young's modulus $E = 170GPa$, and Poissons's ratio $\mu = 0.3$, respectively. A servo-hydraulic fatigue machine was employed for all strain control testing, utilizing a triangular wave with a common strain rate 0.1%/s, Mises equivalent strain rate. 550℃ was gained by the inducing equipment of high frequency. The temperature fluctuation in the gauge is kept ±5℃. Failure is defined as a stress drop 5% comparing with the half life for Mises equivalent stress. The detail test process can be seen in reference [8]. The principal strain ratio ϕ, $\phi = \varepsilon_3 / \varepsilon_1$, is defined. ε_1 and ε_3 are the maximum and minimum principal strains, respectively. $\phi = 0.5$ corresponds to uniaxial fatigue and $\phi = -1$ to torsional fatigue. For the same principal strain ratio, three tests are conducted, especially six tests for $\phi = 0.5$, four tests for $\phi = -1$.

Tab.1 Chemical Composition of Material

Cr	Mo	C	Si	Mn	P	S	Ni	V	Nb	N
8.61	0.93	0.10	0.36	0.37	0.014	0.001	0.08	0.20	0.07	0.057

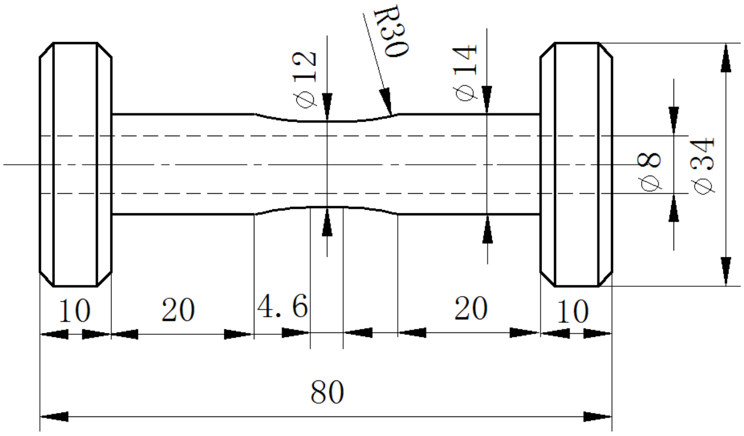


Fig. 1 Shape and dimensions of the specimen

3 CYCLIC PROPERTIES UNDER DIFFERENT STRAIN PATHS AND STRAIN AMPLITUDES

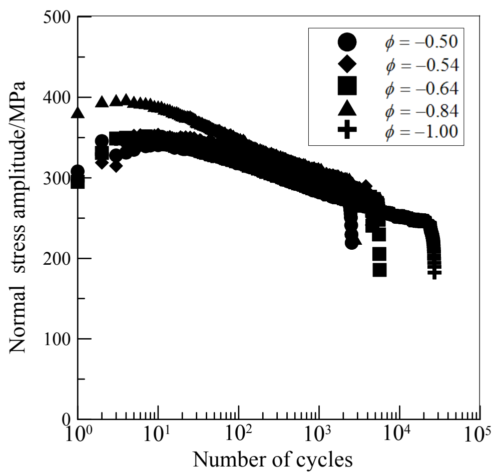


Fig.2 Number of cycles vs Normal stress amplitude ($\Delta\varepsilon_{eq} = 0.5\%$)

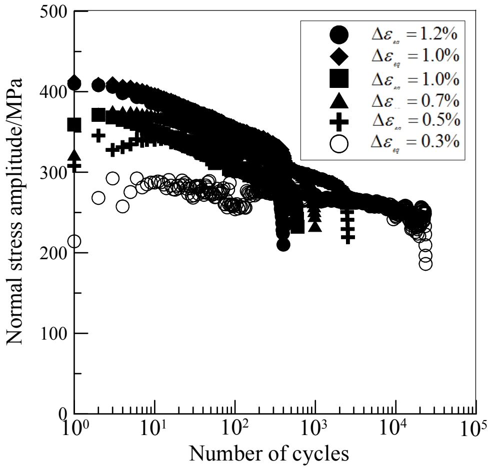


Fig.3 Number of cycles vs Normal stress amplitude($\phi = -0.5$)

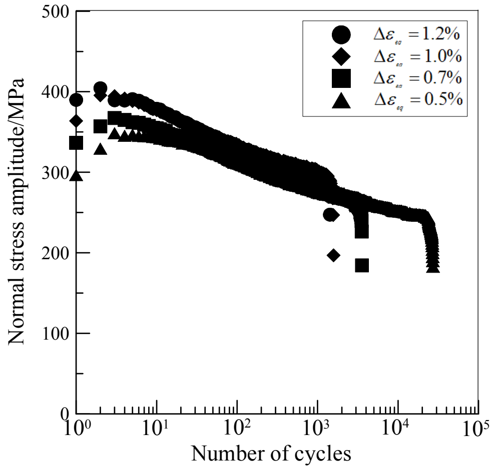


Fig.4 Number of cycles vs Normal stress amplitude ($\phi = -1.0$)

It can be seen from the Fig.2-Fig.4, normal stress increases a little for the original cycles and soon the maximum stress is gained. On the whole, the material shows cyclic softening property for all the strain paths with increase in cycle. This is agreement with the results of reference [5,6]. When $\phi = -0.5$, the cyclic softening property is more obvious with increase in stain amplitude, that is to say, 16.3% for $\Delta\varepsilon_{eq} = 0.3\%$, 22.8% for $\Delta\varepsilon_{eq} = 1.2\%$, and the mean value is 20.7%. The tendency for cyclic softening property increase with the strain amplitude is not obvious in other strain paths. But it can be concluded that the effect of the strain path on the cyclic softening property is more significant than that of strain amplitude. The mean value for cycle softening is 22.9% for $\phi = -0.54$, 26.5% for $\phi = -0.64$, 34.5% for $\phi = -0.84$, 35.3% for $\phi = -1.0$. In principle, the softening phenomenon is more obvious with the torsion loading increase.

4 FATIGUE LIFE PREDICTION APPROACHES AND RESULT DISCUSSIONS

4.1 Fatigue life prediction approaches

The strain approach was the first approach to predict the fatigue life. Recently, energy approach has been employed for fatigue prediction under random loading. An energy model accounting for normal and shear deformation for predicting fatigue lives under variable amplitude multiaxial loading was used by Lee et al.[10](LKN).The critical plane approach is paid more attention by the researchers of all over the world due to the defined physical background. Smith et al.[11](SWT)proposed a fatigue model for materials showing normal fracture. The maximum normal strain plane was considered as the critical plane in the model. Wang and Brown[12] applied the Kandil-Brown-Miller[13](KBM) model to variable amplitude tension-torsion loading with the maximum shear strain range plane as the critical plane. Fatemi and Socie[14](FS) proposed a fatigue model for shear fracture materials. The maximum shear strain plane was considered as the critical plane and the normal stress on the plane was used to replace the normal strain of the KBM model. Chen, Xu and Huang[15] proposed a critical plane criterion by considering the effect of normal stress, normal strain, shear stress and shear strain on fatigue life.

The equivalent strain approach, energy approach, and critical plane approaches are shown in Tab.2.

Tab.2 Approaches for fatigue life prediction

Approach		Formula	Material constant
Equivalent strain approach		$\frac{\Delta\varepsilon_{eq}}{2} = \frac{\sigma_f'}{E}(2N_f)^b + \varepsilon_f'(2N_f)^c$	
Energy approach LKN		$W_e^* = \frac{1}{2E}(\frac{\Delta\sigma_n}{2})^2 + w\frac{1}{2G}(\frac{\Delta\tau_n}{2})^2$, $W_p^* = \int_{cycle}\sigma_n d\varepsilon_n^P + w\int_{cycle}\tau_n d\gamma_n^p$ $W_e^* = \frac{(\sigma_f' - \sigma_n^0)^2}{2E}(2N_f)^{2b}$, $W_p^* = 4(\sigma_f' - \sigma_n^0)\varepsilon_f'\frac{c-b}{c+b}(2N_f)^{b+c}$	$w = 0.5$
Critical plane approach	SWT	$\frac{\Delta\varepsilon_n}{2}\sigma_n^{\max} = \frac{\sigma_f'^2}{E}(2N_f)^{2b} + \sigma_f'\varepsilon_f'(2N_f)^{b+c}$	
	FS	$\frac{\Delta\gamma_{\max}}{2}(1 + k\frac{\sigma_n^{\max}}{\sigma_y}) = \frac{\tau_f'}{G}(2N_f)^{b_0} + \gamma_f'(2N_f)^{c_0}$	$k = 1.5$
	KBM	$\frac{\Delta\gamma}{2} + s\varepsilon_n^* = [1 + \upsilon + (1-\upsilon)s]\frac{\sigma_f' - \sigma_0}{E}(2N_f)^b + (1.5 + 0.5s)\varepsilon_f'(2N_f)^c$	$s = 2.0$
	CXH	$\Delta\varepsilon_1^{\max}\Delta\sigma_1 + \Delta\gamma_1\Delta\tau_1 = 4\frac{\sigma_f'^2}{E}(2N_f)^{2b} + 4\sigma_f'\varepsilon_f'(2N_f)^{b+c}$	

In previous formulas, $\sigma_f'(\tau_f')$, $\varepsilon_f'(\gamma_f')$, $b(b_0)$ and $c(c_0)$ are the material constants in Coffin-Manson equation. They can be gained from the uniaxial and torsional test results. The fitting result can be observed in Tab. 3.

Tab.3 Fatigue properties of the material

	$\sigma_f'(\tau_f')$ (MPa)	$\varepsilon_f'(\gamma_f')$	$b(b_0)$	$c(c_0)$	$E(G)$ (MPa)
Tension-	500	0.580	-0.064	-0.770	170000

compression					
Torsion	299	0.165	-0.069	-0.400	65000

4.2 Discussions for prediction results

The strain approach was the first approach to predict the fatigue life and the acceptable prediction results could be gained under proportional loading for many materials. But for the material in this paper, the prediction results of equivalent strain approach are more conservative, Fig.5. From the previous results, it can be seen that the cyclic softening property is obvious under the torsion loading, $\phi = -1.0$. The fatigue life is three times under torsion loading than that of uniaxial loading for the same equivalent strain amplitude, even ten times for smaller strain amplitude. So the prediction results are more conservative with ϕ decrease.

For LKN approach, the energy parameter is considered as the damage parameter. For this material, the fatigue life is given based on the maximum shear strain plane and the prediction results are better than that of other approaches. It can be seen from Fig.6.

The maximum normal strain plane is considered as the critical plane in SWT approach and the calculation is given based on it. The nonconservative results are given for $\phi = -1.0$, Fig.7. The prediction results of FS approach are seen in Fig.8. The cyclic property can be explained by considering the normal stress on the critical plane and the prediction results are better although the prediction results for some strain paths are not safe. The prediction results for KBM approach are little conservative than that of FS approach, Fig.9. The shear strain and shear stress are considered in CXH approach so the prediction results for CXH are better than SWT (Fig.10). On the whole, the fatigue results are better based on the maximum shear strain plane as the critical plane.

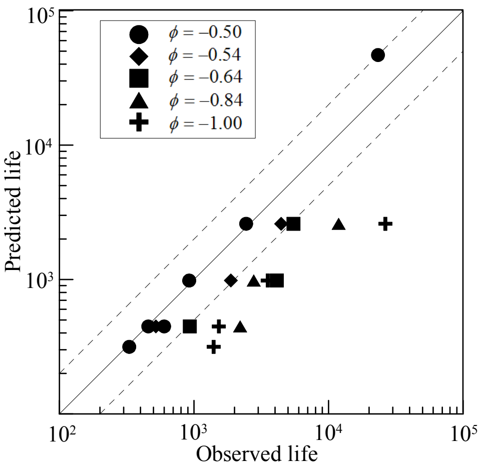


Fig. 5 Prediction results for equivalent strain approach

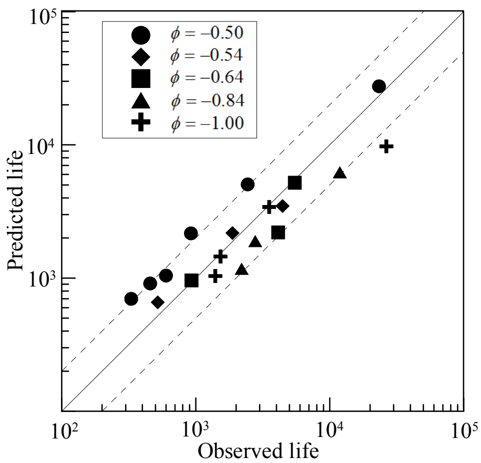
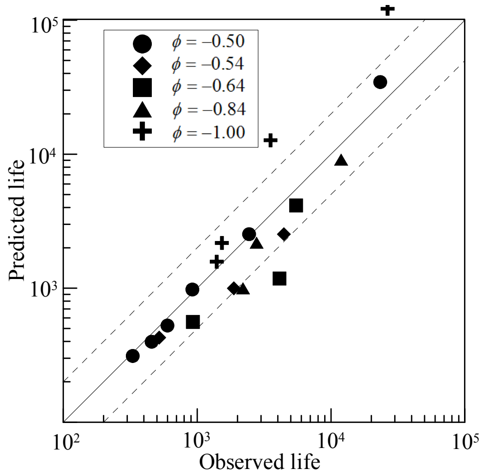


Fig. 6 Prediction results for LKN approach



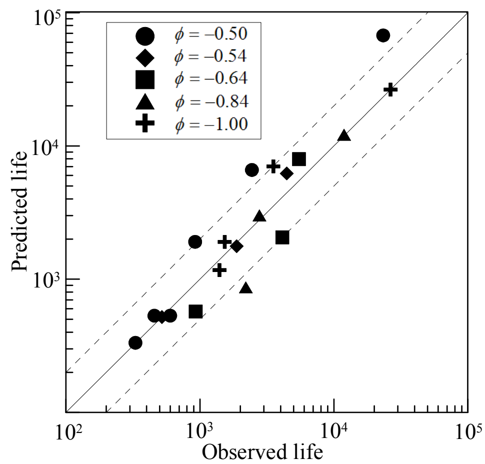
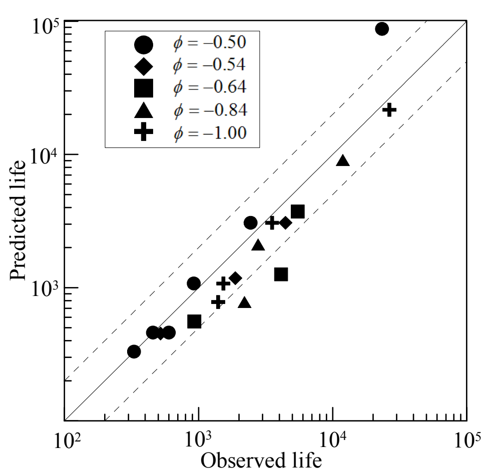


Fig.7 Prediction results for SWT approach Fig. 8 Prediction results for FS approach



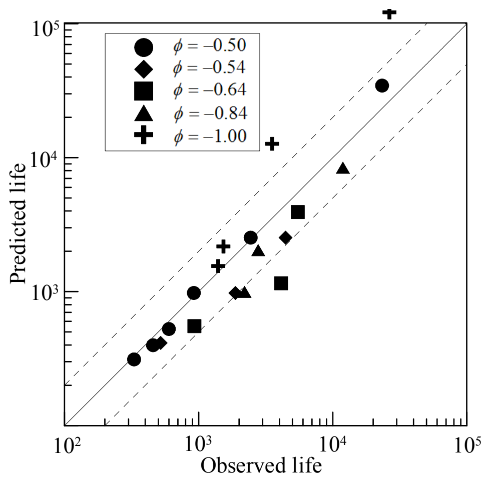


Fig. 9 Prediction results for KBM approach Fig. 10 Prediction results for CXH approach

5 CONCLUSIONS

(1) A series of fatigue tests are conducted for Mod.9Cr-1Mo ferrite steel under uniaxial and multiaxial loading at 550℃. The effect of strain multiaxiality on the fatigue life for proportional loading is considered by defining the principal strain ratio.

(2) The cyclic property for this material is discussed under different strain paths. It is showed that the softening property is observed at high temperature for all the strain paths. The loading path has more effect on the softening property than that of the strain amplitude. The cyclic softening degree are 20.7%, 22.9%, 26.5%, 34.5%, and 35.3% for $\phi=-0.5$, $\phi=-0.54$, $\phi=-0.64$, $\phi=-0.84$, and $\phi=-1.0$,respectively.

(3)The fatigue life predictions show that the results for equivalent strain approach are too conservative, excellent for LKN approach. The results for SWT are nonconservative for the torsion path. The prediction results for FS model and KBM model are satisfying and the prediction results for CXH approach are better than that of SWT.

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