Transactions, **SMiRT-22**
San Francisco, California, USA - August 18-23, 2013
Division I (include assigned division number from I to X)

CYCLIC ASYMMETRY BEHAVIOR OF MARTENSITIC STEELS AT HIGH TEMPERATURES

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ABSTRACT

Low cycle fatigue tests of a modified 9Cr–1Mo steel under total strain controlled conditions were conducted at 773K and 873K.The total strain amplitudes varied from ±0.2% to ±1.2% with a strain rate of 0.8%/s. The cyclic stress response behavior showed a continuous and gradual softening up to the specimen failure. The cyclic asymmetry deformation behavior was observed between the compression and tension process. An asymmetry factor was defined to reflect the effect of strain amplitude and temperature. Compared the monotonic and cyclic stress-strain curves, it is found that cyclic softening restrained the asymmetry. In terms of the evolution of the internal stresses, the difference of the tension and compression back stress should be responsible for the asymmetry behavior.

INTRODUCTION

The modified 9Cr-1Mo martensitic steel has been used in power generation systems due to its high thermal conductivity and low thermal expansion coefficient (Swindeman et al.,2004). Steam turbine rotors as the key components of turbine unit are often subjected to low cycle fatigue damage caused by repeated thermal stresses that occur on heating and cooling during start-ups and shutdowns or during variations in operating conditions.

The low cycle fatigue behavior of martensitic steels has been reported by many studies (Nagesha et al., 2002; Fournier et al., 2006; Kim and Kim,2012),which showed that the cyclic softening occurred during cyclic deformation. Careful observation on the cyclic peak stresses reveals that the value of the compression stress always exceeds that of the tension stress, which is called tension-compression asymmetry or the strength differential effect. The experimental observations of this behavior in different materials have been the subject of some studies. Meininger et al. (1996) investigated the tension-compression asymmetry behavior in the cyclic deformation of aluminum alloy 7075 in the T6 and T651 tempers. They found that the degree of initial asymmetry for both tempers of this alloy was dependent on plastic strain amplitude while the asymmetry at saturation remained relatively constant. Yaguchi and Takahashi (2005) conducted a series of monotonic compression tests on modified 9Cr–1Mo steel and compared the results with corresponding tensile data. Their results demonstrated that the material showed tension/compression asymmetry, which resulted in a anomalous ratchetting observed in the uniaxial ratchetting tests, and might be accelerated by the cyclic softening behavior. In a word, the asymmetry exists extensively in different materials, such as martensitic stainless steels (Hirth and Cohen,1970), austenitic stainless steel (Chiou,2010), aluminum alloys (Hörnqvist and Karlsson,2008) and magnesium alloys (Yu et al.,2012). The conventional approach to analyze the cyclic stress response is in terms of the variation of the stress amplitude or only the tension peak stress with the number of cycles during LCF deformation. Few studies discussed the tension and compression peak stresses separately, which can bring out the tension/compression asymmetry. So the conclusions drawn from the cyclic stress response might not be entirely accurate. Meanwhile, the study on the effect of cyclic stress response on that tension/compression asymmetry behavior was seldom concerned in the existed literatures.

As for the cause of tension/compression asymmetry behavior, many attempts have been conducted so far. Meininger et al.(1996) pointed out that the asymmetry cannot be attributed to cross-section change during tension and compression since this effect is taken into account by the calculation of true stress and true strain throughout the tests. They also eliminated the possibility that the asymmetry is related to inaccuracies in the testing procedures and testing machine. In the work of Meininger(1996) and Pampillo(1972), a nonlinear elastic strain contribution was presented to consider the asymmetry observed in the hysteresis loop shape. The nonlinear relation at larger elastic strain resulted in the difference of effective modulus in compression and in tension. Pampillo explained quantitatively the asymmetry behavior by separating the applied flow stress into internal stress and effective stress. They attributed the asymmetry to the influence of the effective modulus on the internal stress. However, Meininger showed that the nonlinear elastic term does not completely account for the asymmetric peak stresses. Then they attributed the asymmetry to strain localization as a consequence of quench band formation and precipitate cutting during straining. Hirth and Cohen(1970) summarized various theories to explain the asymmetry behavior including microcrack, residual stress, internal Bauschinger effect, volume expansion due to plastic deformation and solute/dislocation interaction, wherein the last mentioned hypothesis was proposed. Ma et al.(1990) ascribed the asymmetry of pure polycrystalline copper during cyclic deformation to the localized deformation in soft lamellae embedded in a harder matrix. They further proposed that the degree to which the hard phase constrains the softer phase is less in tension than in compression, resulting in the observed asymmetry. It is important to note that the quantitative description between the asymmetry and inhomogeneous deformation should be built to adequately understand the asymmetry behavior.

In this work, a detailed investigation on the tension compression asymmetry behavior during fatigue deformation for a martensitic steel under strain controlled conditions at high temperatures was carried out. The results pertaining to the strain amplitude and temperature dependent evolution of the asymmetry, to the effect of cyclic stress response and also to the origin of the asymmetry behavior by analyzing changes of internal stresses were presented and discussed in the following sections.

EXPERIMENTAL PROCEDURES

The materials used in this study were the wrought martensitic stainless steels X12CrMoWVNbN10-1-1(X12). The chemical composition of X12 (wt.%) is given in Table 1. Table 2

Table 1 Chemical compositions of X12 (wt.%)

Materials	C	Si	Mn	P	S	Ni	Cr	Mo	V	W	Nb	N
X12	0.12	0.10	0.42	0.007	0.001	0.76	10.7	1.04	0.16	1.04	0.05	0.056

Table 2 Mechanical properties of X12

	273K	773K	873K
Elastic modulus(GPa)	213	173	136
Yield strength $\sigma_{0.2}$,MPa	765	589	456
Ultimate tensile strength σ_b MPa	878	648	475
Elongation δ,%	11.5	20.1	31.7
Reduction of area ψ， %	62.5	65.2	82.1

shows the mechanical properties at different temperatures. Fatigue specimens were machined to cylindrical specimens with a uniform gauge section of 10mm in diameter and 14mm long as shown in Fig.1. Before mechanical testing the surface of the gauge section was polished using emery paper up to mesh #1500 for attaining smooth surface.

Total strain controlled low cycle fatigue tests were performed on Instron 8032 servo-hydraulic machine equipped with a heating furnace. Nominal strain was measured and controlled with a clip-on extensometer with an axial 12.5mm gauge length attached to the test specimen at the gauge section. The LCF tests were conducted under fully-reversed tension-compression loading (strain ratio R=-1). The controlled total strains were selected in the range from ±0.2 to ±1.2% with a strain rate of 0.8%/s at 773K and 873K in ambient atmosphere. The fatigue life represented the number of cycles when the load decreased 40% in 50 cycles.

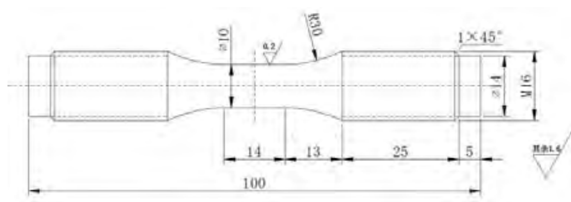


Fig. 1 Low cycle fatigue specimen

RESULTS AND DISCUSSION

Cyclic Stress Response

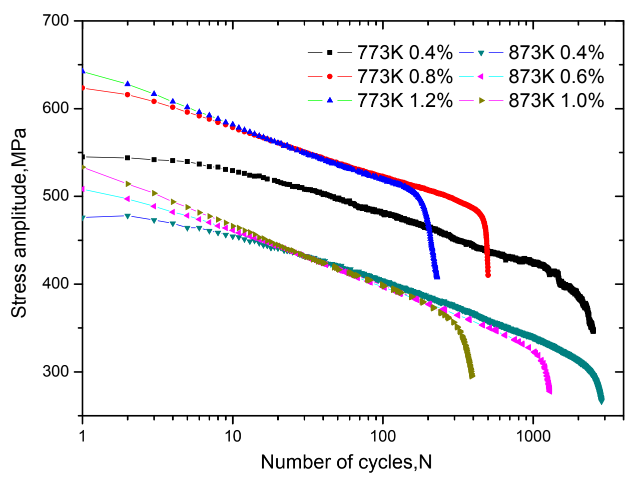


Fig.2 Evolution of the stress amplitude during LCF testing of X12 at 773K and 873K

In Fig.2, the stress amplitudes are plotted as a function of number of cycles. The cyclic stress response behavior for all the strain amplitudes tests shows a continuous and gradual softening up to the specimen failure. The fatigue life became shorter but the stress amplitude increased with increasing strain amplitude. The higher the strain amplitude is, the faster and the stronger the cyclic softening is. The stress response and the number of cycles to failure decreased and the cyclic softening was more prominent with increasing temperature as shown in Fig.2. At 873K the cyclic stress response was independent of the strain amplitude in the second stage for strain amplitude above 0.4%.

Tension/Compression Asymmetry

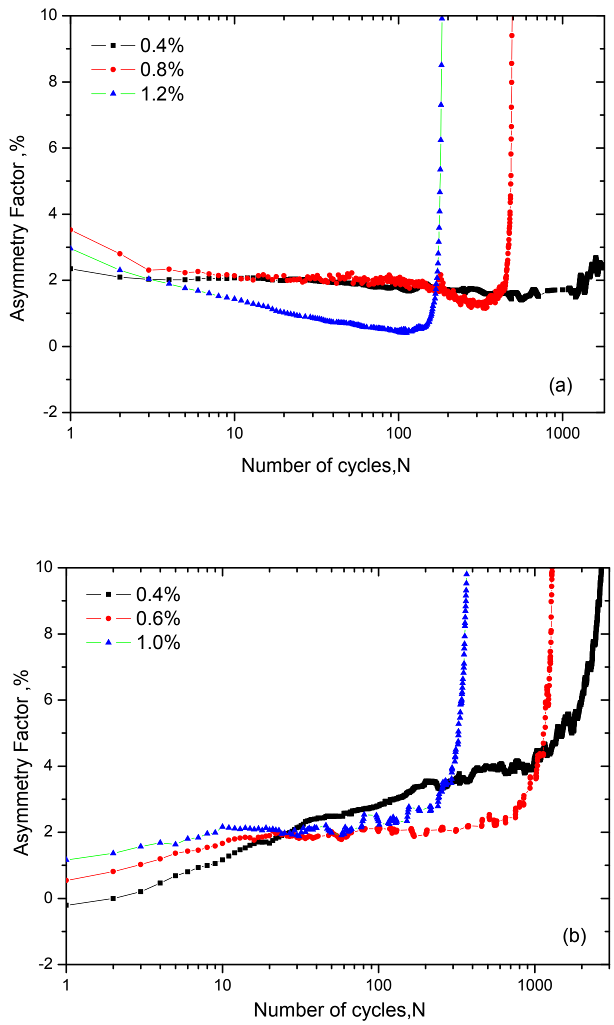
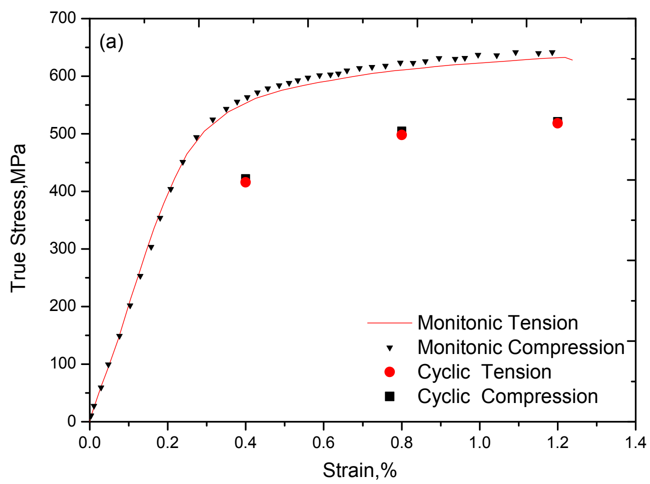


Fig.3 Variation of the asymmetry factor with the number of cycles at (a)773K and (b)873K

The analysis of the cyclic stress response failed to take into account the evolution of tension and compression peak stress. For all the strain amplitudes tested, the compression peak stresses were greater than the tension peaks for present martensitic steel. In order to characterize this asymmetry behavior, it was effective to adopt the asymmetry factor defined by Ma et al. (1990):

$$A = \frac{(|\sigma_c| - |\sigma_t|)}{(|\sigma_c| + |\sigma_t|)/2} \tag{1}$$

where σ_c is the true compression peak stress and σ_t is the true tension peak stress. All true stresses described in the present paper are determined from the measured engineering stresses. The asymmetry factor as a function of number of cycles is illustrated in Fig.3. Although the magnitude of asymmetry factor is small, a specific trend is seen. It is apparent that the material shows different evolutions of asymmetry behavior with cyclic number at these two temperatures. At 773K, the asymmetry factor decreases gradually for the first few cycles to a relatively stable value. The extent of initial asymmetry is independent of the strain amplitude. The stable value decreases with increasing strain amplitude, similar to the results of Mercer et al.(1995) . At 873K, the asymmetry factor increases gradually in the early stage of fatigue life. The initial asymmetry factor depends on the strain amplitude. Indeed, the higher strain amplitude, the larger the initial asymmetry factor but the smaller the saturation value. The temperature dependent evolution of the asymmetry may be due to the activation volume of dislocation movement (Ko and Kim,2012).The asymmetry factor as a function of the strain amplitude at saturation for both temperatures is quite similar to that observed by Meininger(1996) for AA7075 -T6 temper. With increasing strain amplitude, deformation becomes more homogeneous as a consequence of the activation of cross-slip and secondary slip facilitated by the higher stresses, which results in the smaller asymmetry factor at higher strain amplitudes. As cycling proceeds, tension load carrying area decreased with expanding cracks, the degree of compression load carrying area decreasing was smaller due to the closure of the intrinsic cracks in the specimen. So with a severe loss of tension load carrying capability, the sharp upturn near the end of the test can be observed as shown in Fig.3.



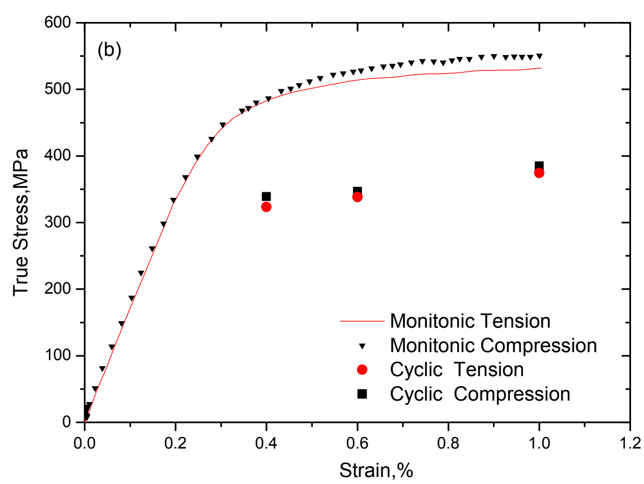


Fig.4 The monotonic as well as cyclic stress-strain relationship at (a)773K and (b)873K

A series of monotonic tension and corresponding compression tests were conducted in order to determine further the asymmetry behavior of tensile and compressive responses. The monotonic and cyclic stress-strain response at 773K and 873K can be represented as shown in Fig.4. The difference of monotonic tension and compression stress is similar to those observed under the cyclic conditions. The compression stress always exceeds the tension stress in the inelastic deformation region. It is concluded that deformation resistance under compression stress is larger than that under tension stress. The difference increased with increasing strain amplitude， which is exactly opposite to that in cyclic condition. The higher the temperature is, the larger tension-compression difference is during the monotonic deformation. Fig.4 also exhibits the cyclic tension and compression peak stress at different applied strains. Each data was taken at the half of its fatigue life. The degree of the tension/compression asymmetry during cyclic deformation is generally smaller than that during the monotonic deformation, which may come from the retardation of cyclic softening.

Physical Origins of Asymmetry

In the present work, nonlinear elastic response, as reported by Meininger and Pampillo, is not obvious in the hysteresis loop shape. A detailed analysis for the hysteresis loops ,as proposed by Cottrell (Fournier et al,2006), was carried out to determine the mechanisms responsible for the tension-compression asymmetry behavior. The peak stress can be partitioned into back stress σ^i and effective stress σ^* . Generally speaking the back stress is the directional component of the stress which corresponds to long range interactions with piled-up dislocations. Applied stress has to overcome back stress to initiate dislocation motion. The effective stress required to overcome short range obstacles is equivalent to the resistance which the dislocations have to overcome to keep moving in the lattice, which is the driving force for dislocation motion (Reddy et al.,2010).

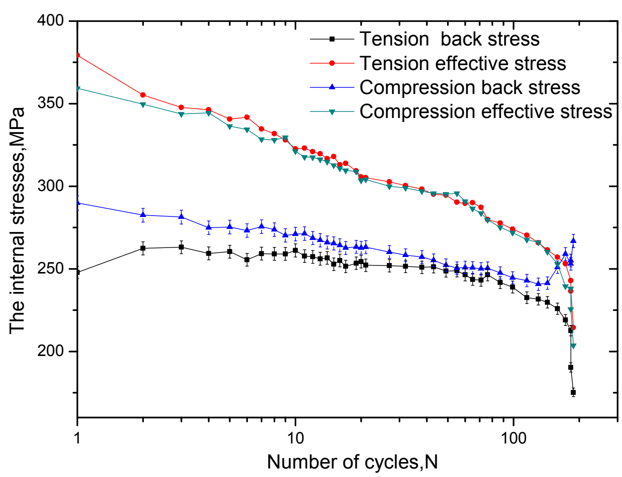


Fig.5 Evolution of back and effective stress during cycling in LCF tested (T=773K and $\Delta\varepsilon_t = 1.2\%$)

The variation of the tension and compression internal stresses with the number of cycles at T=773K and $\Delta\varepsilon_t = 1.2\%$ is shown in Fig.5. The magnitude of these stresses is described with the error band of 3% due to the error of the method. In spite of this inaccuracy, the trends of the variation of internal stress with cycling are definite. As shown in Fig.5, the compression effective stress is close to the tension effective stress. However, significant difference of tension and compression back stress is observed as cycling proceeds, which is in agreement with the evolution of the corresponding asymmetry factor. In order to validate this correlation, the strength differential effect of back stress and effective stress between tension and compression is plotted in Fig. 6. Compared with the differential of peak stress as shown in Fig. 6, it is found that the differential of back stress is almost equal to that of peak stress, but the differential of effective stress is a constant near zero during cyclic deformation except for the first few cycles of fatigue life. So it was concluded that the tension-compression asymmetry observed on martensitic steels was mainly, if not entirely, carried by the tension-compression differential of the back stress, regardless of the temperature and the strain amplitude. The back stress is associated with piled-up dislocations. In compression, the mobile dislocations move in a reverse manner and pile up against dislocation cell wall on the opposite side ,compared with tension (Kim and Kim,2012). In conclusion, deformation resistance that was created by the dislocations movement under compressive condition is somewhat larger than that under tension, which resulting in the tension-compression asymmetry.

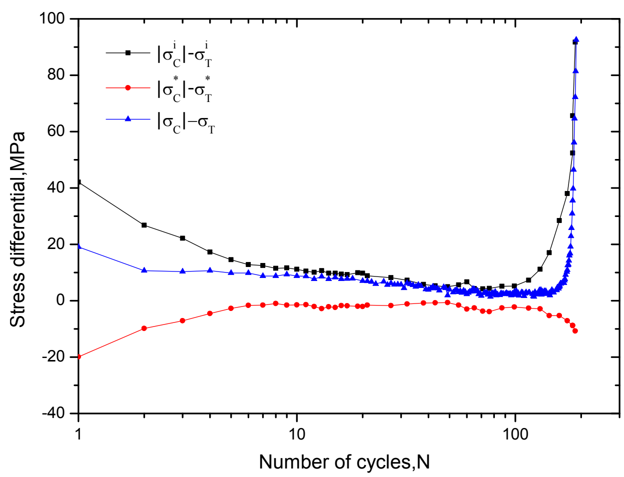


Fig.6 Evolution of strength differential of back stress, effective stress and peak stress during cycling

CONCLUSIONS

In the present study, the cyclic tension-compression asymmetry behavior of a martensitic steel steel was investigated under fully-reversed strain controlled conditions at high temperatures. The main findings can be summarized as follows:

1. At 773K, the initial asymmetry factor is independent of the strain amplitude and decreases gradually for the primary few cycles to a relatively stable value, which decreases with increasing the strain amplitude. In contrast, the asymmetry factor increases gradually in the early stage of fatigue life at 873K. The higher strain amplitude, the larger the initial asymmetry factor but the smaller the saturation value.
2. The value of the cyclic asymmetry is generally smaller than the monotonic asymmetry due to cyclic softening effect during cyclic deformation.
3. The tension-compression asymmetry observed on martensitic steels during cyclic deformation is at least partially carried by the difference of the back stress as a result of long range interactions with piled-up dislocations in the process of tension and compression.

Acknowledgements

The authors are grateful for the supports provided by The National High Technology Research and Development Program of China (2012AA040106), National Key Technology R&D Program (2011BAK06B03) and the Natural Science Foundation of Shanghai (11JC1403200).

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