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Uniaxial mean stress relaxation of 9–12% Cr steel at high temperature: Experiments and viscoplastic constitutive modeling

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ABSTRACT

Symmetrical and asymmetrical strain cycling tests of X12CrMoWVNbN10-1-1 steel were conducted at 873 K. Significant rate dependence, mean stress relaxation and continuously cyclic softening behavior were observed during the fatigue process. In addition, a strain-amplitude dependent competition between cyclic softening and mean stress relaxation was revealed. When the strain amplitudes were larger than the initial plastic point, the cyclic softening was dominated with a rapidly relaxed mean stress and a significantly altered hysteresis loop during the primary cycles. Whilst for the strain amplitudes being less than the initial plastic point, the continuously relaxed mean stress with unclearly altered hysteresis loops was observed during the whole lifetime. Accordingly, a new cyclic viscoplastic constitutive is proposed through the combination of a new nonlinear kinematic hardening rule and the Abdel-Karim–Ohno model. The strain-amplitude dependent cyclic softening and mean stress relaxation behavior were finely reproduced by the proposed model, which was achieved by introducing a mean stress relaxation parameter as a function of the maximum plastic strain and the accumulated cyclic plastic strain.

1. Introduction

Modified 9–12% Cr martensitic steels have been widely used in high temperature components of power plant due to the high thermal conductivity and the low thermal expansion coefficient (Swindeman et al., 2004). Since these components (such as rotor, cylinder, pipes etc.) are often subjected to the repeated thermal and mechanical stress, fully understanding of fatigue properties of the modified 9–12% Cr martensitic steel is quite important in the life design and the reliability assessment of structures. Especially in the local critical area of components, limited plastic flow phenomena like the cyclic ratcheting (under the stress-control condition) or the cyclic stress relaxation (under the strain-control condition) may arise and need to be described accurately in terms of cyclic plastic or viscoplastic constitutive equations.

During the last two decades, considerable effort has been devoted to the cyclic ratcheting and cyclic stress relaxation behavior of modified 9–12% Cr martensitic steels under either the stress- or strain-controlled conditions. Under the symmetrical cycling condition, Nagesha et al. (2002), Yaguchi and Takahashi (2005a), Fournier et al. (2006), Saad et al. (2013), Golański and Mroziński (2013), Guguloth et al. (2014) and Wu et al. (2015) conducted the fully reversed low cycle fatigue

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experiment. For the plastic flow phenomena under the asymmetrical stress-controlled condition, Abdel-Karim and Ohno (2000), Koo and Lee (2007), Kunz and Lukáš (2001), Ohno and Wang (1993), Tanaka and Yamada (1993), Yaguchi and Takahashi (2005a), Zhao and Xuan (2011, 2012) investigated the ratcheting behavior of 9–12% Cr steel experimentally. The existing experimental results of modified 9–12% Cr steels have revealed that:

- Significant ratcheting in the tensile direction is detected even under the zero mean stress condition (Yaguchi and Takahashi, 2005a; Wu et al., 2015).
- Ratcheting strain and the steady ratcheting rate increase with the increase of applied mean stress (at a given stress amplitude) and stress amplitude (at a given mean stress) (Kunz and Lukáš, 2001; Koo and Lee, 2007);
- Cyclic softening behavior is produced continuously during the whole fatigue life and increases with the increase of temperature and the repeated loading amplitude (Nagesha et al., 2002; Golański and Mroziński, 2013; Guguloth et al., 2014);
- Under the multiaxial condition, lower ratcheting is often observed compared with the corresponding equivalent uniaxial loading (Yaguchi and Takahashi, 2005a).
- Ratcheting behavior is significantly affected by the prior loading history. For instance, the uniaxial ratcheting can be accelerated largely when the cyclic deformation has been given before the ratcheting test (Yaguchi and Takahashi, 2005a).

Along with the above features of ratcheting observed experimentally, several new constitutive models have been developed (Ohno and Wang, 1993; Tanaka and Yamada, 1993; Abdel-Karim and Ohno, 2000; Yaguchi and Takahashi, 2005b; Koo and Lee, 2007; Zheng et al., 2011). As reviewed by Ohno (1990), Khan and Huang (1995), Chaboche (2008) and Kang (2008), these existing constitutive models are mainly developed from the Prager's linear kinematic hardening model (Prager, 1956) and can be generally classified into two groups. The first one is based on the non-linear kinematic hardening rule which is initiated by Armstrong and Frederick (1966) and generally simplified as the A-F model. The second one is based on the two surface model established firstly by Mroz (1967) and then improved by Dafalias and Popov (1976). Comparatively, these A-F type models have advantages over the latter one in simulating the ratcheting response using the concept of strain hardening and dynamic recovery and have been extensively worked out by many authors (Chaboche, 1989, 1991, 1994; Ohno and Wang, 1993; McDowell, 1995; Jiang and Sehitoglu, 1996; Yaguchi and Takahashi, 2000; Abdel-Karim and Ohno, 2000; Bari and Hassan, 2000, 2002; Kang et al., 2002, 2003; Chen and Jiao, 2004; Chen et al., 2005; Yu et al., 2012). Nevertheless, it is well recognized that the correct description of ratcheting effects is still one of the most difficulty in material behavior simulation.

As one of the critical plastic flow phenomenon under the strain-controlled condition, mean stress relaxation has been identified as the same mechanism as ratcheting (Jhansale and Topper, 1973). Compared to the ratcheting behavior under the stress-controlled condition, however, less systematical studies are conducted on the mean stress relaxation effect under the strain-controlled condition. Experimental studies conducted by Arcari et al. (2009), Chiou and Yip (2003), Chiou (2010), Colin et al. (2010), Ellyin (1985), Fang and Berkovits (1994), Hao et al. (2015), Kabir and Yeo (2012), Koh and Stephens (1991), Lin and Chu (2000) and Wehner and Fatemi (1991) have provided the valuable information for mean stress relaxation characteristics of various materials. It has been realized that the rate of relaxation, the amount of relaxation and the stable value depend on the strain amplitude, strain ratio and materials. For example, under the large strain amplitude, the mean stress will disappear completely during the primary several cycles and hence has an insignificant detriment of fatigue life (Fang and Berkovits, 1994; Koh and Stephens, 1991; Lin and Chu, 2000; Wehner and Fatemi, 1991). Under the low strain amplitude, by contrast, the relaxation of mean stress is very limited and unavoidably imposes a detrimental effect on the fatigue life. Unfortunately, for the modified 9–12% Cr steel with significant cyclic softening, up to now, much less experimental studies on the cyclic stress relaxation have been published.

As for the modeling on the cyclic stress relaxation behavior, very limited works have been published involving the strain-controlled history (Chaboche and Jung, 1998; Chaboche et al., 2012; Gustafsson et al., 2011; Hu et al., 1999; Kourousis and Dafalias, 2013; Lee et al., 2014; Yeom et al., 2001). Generally, these existing models are mainly improved from the A-F nonlinear kinematic hardening rule through introducing the “dynamic recovery” term. These developed kinematic hardening rules differ on decomposing the back stress (Hu et al., 1999), introducing the threshold (Chaboche et al., 2012; Gustafsson et al., 2011; Yeom et al., 2001), incorporating the accumulated plastic strain increment (Lee et al., 2014), combining the linear kinematic hardening (Yeom et al., 2001) and so on. In addition, it has been deemed that such models are capable of providing accurate simulation of ratcheting phenomenon should have also the potential for a correct prediction of cyclic mean stress relaxation (Chaboche et al., 2012; Lee et al., 2014). For example, Kourousis and Dafalias (2013) have checked the applicability of the multi-component A-F multiplicative (MAFM) model (initiated by Dafalias et al., 2008) in the simulation of cyclic mean stress relaxation of Aluminum alloy 7050. However, the capability of these ratcheting models to reproduce the mean stress relaxation is mainly limited to the case of large strain ranges where the mean stress relaxes and vanishes rapidly. Recently, Chaboche et al. (2012) have improved the multi-kinematic hardening rule through involving the threshold effect and the stabilized mean stress is well reproduced in a wide range of strain amplitudes. However, our recent study (Zhao et al., submitted for publication) indicates that different mechanisms of cyclic softening of modified 9–12% Cr steels are involved in strain- and stress-controlled modes. This can be reflected by the more significant softening in the stress cycling than that in the strain cycling. It also indicates that the ratcheting constitutive model developed from the stress-controlled condition cannot be employed directly to predict the mean stress relaxation behavior in some cases.