Cyclic behaviour and plastic strain memory effect of 55NiCrMoV7 steel under low cycle fatigue

Zhang Zhanping, Denis Delagnes, Gérard Bernhart

Cyclic behaviour and plastic strain memory effect of 55NiCrMoV7 steel under low cycle fatigue

ZHANG Zhanping[a], Delagnes D[b], and Bernhart G.[b]

[a] *Department of Materials Science & Engineering, Dalian Maritime University, Dalian 116026, China*

[b] *Institute Clément Ader EA814, Ecole des Mines d'Albi-Carmaux, 81013 Albi CT cedex 09, France*

Abstract

Cyclic plastic behaviour of tempered martensitic tool steel 55NiCrMoV7 with four different initial hardness levels was studied under tensile-compress low cycle fatigue (LCF) in the temperature range from room temperature up to 873 K. Cyclic behavior tests and strain memory effect tests were performed in symmetrical tensile-compression strain loading with a triangular waveform. The results show that steel represents cyclic softening behaviour. The cyclic stress response generally shows an initial exponential softening for the first few cycles, followed by a gradual softening without saturation. Cyclic stress response depends on strain rate. The steel represents cyclic viscoplasticity. The steel shows the plastic strain memory effects at each test temperature, the cyclic stress and cumulated plastic strain depends on the history of cyclic loading. If strain amplitude increases after a previous linear softening is achieved, a new rapid non-linear cyclic softening appears. In the opposite, if strain amplitude decreases from higher one to lower, softening remains linear, and moreover σ-p curve goes along the previous way at the previous same strain loading level. It was discussed that the influences of initial hardness, fatigue temperature, strain rate and cyclic strain amplitude on cyclic plasticity of the steel.

Keywords: low cycle fatigue; plastic strain memory effect; steel; cyclic softening

1. Introduction

Hot-work tool steels are widely used at various heat-treatment (i.e. tempering conditions) states to obtain the mechanical properties requested by the industrial application, like hot forging, hot-rolling, extrusion, where the steel endures cyclic thermal and mechanical loads [1]. Most of the investigations indicate that fatigue is responsible, in parallel to wear and abrasion, of tool limit lifetime [2-4]. Nevertheless lifetime of steels not only depends upon its service conditions such as temperature [4-6], frequency [7-10], stress ratio [11], strain amplitude [12-14] etc., but also upon cyclic plasticity [15-16] and microstructure [3-5,8-9] which can be controlled by means of heat treatment. The studies of the 429EM steel in [17] and [18] revealed a memory effect of the plastic strain amplitude which can be also simulated by a constitutive model. It is important to understand well the cyclic plastic behaviour of steel under low cycle fatigue (LCF) for the aim to prolong the lifetime of hot-work tools. This paper reports on LCF experimental results and cyclic plastic behaviour of the steel 55NiCrMoV7 with different hardness tempered.

Corresponding author: ZHANG Zhanping **E-mail:** zzp@dlmu.edu.cn

2. Experimental

Isothermal fatigue behaviour of the steel was investigated for each tempering state in the range from ambient to 873 K. All fatigue tests were carried out with a MTS 810 closed-loop servo-hydraulic testing machine. LCF test details could be found in the reference [19]. Two type tests were carried out as following:

Cyclic behaviour test: total strain amplitude is fixed to $\Delta\varepsilon_t = \pm 0.8\%$ during all the tests at constant strain rate 1×10^{-2} s^{-1} during a first phase. After cumulated plastic strain "p" close to 4 mm/mm, in other words, the material has reached the quasi-linear cyclic softening stage, three levels of strain rates from 1×10^{-2} s^{-1} to 1×10^{-3} s^{-1} and 1×10^{-4} s^{-1} were tested for only three cycles at each strain rate. This test is used to understand the effect of temperature and total strain rate on cyclic behaviour of steel.

Strain memory effect test: total strain amplitude $\Delta\varepsilon_t$ was changed in the following sequence: ± 0.6%, ± 0.7%, ± 0.8%, ± 0.9%, and ± 0.7% at constant strain rate 10^{-2} s^{-1}. The number of cycles performed at each strain amplitude level was selected to reach a cumulated plastic strain "p" close to

1 mm/mm. This test is used for studying the cyclic plastic strain memory behaviour.

3. Results and discussion

3.1. Cyclic behaviour

The typical cyclic behaviour of the 55NiCrMoV7 steel was showed in Fig. 1 by the $\Delta\sigma_i/\Delta\sigma_1$-p curves. When the hardness of the steel and LCF test temperature were low, as showed in Fig. 1 (a) and (b), the steel manifests the behaviour of cyclic softening under the loading of cyclic strain. When the hardness of the steel and LCF test temperature were high, as showed in Fig. 1 (c) and (d), although the steel manifests a little cyclic hardening during only initial several cycles, but the steel manifests the behaviour of cyclic softening as a whole. Therefore, this cyclic softening of the steel could be divided into two phases, which are the rapid softening phase during the initial stage of cyclic strain (cumulated plastic strain ≤ 1) and following the slow softening phase (cumulated plastic strain > 1) without cyclic saturation. The former is generally explained by the exponential change of the density and structure of dislocations. Generally speaking, the latter is related to the modification of dislocation sub-structure and carbide in the steel by the action of cyclic load.

Considering the second phase of the cyclic behaviour tests (three cycles at strain rates respectively equal to 10^{-2}, 10^{-3} and 10^{-4} s^{-1}), stress-strain hysteresis loops showed, like as in Fig. 2 (a) for 42HRC at 873 K, that the cyclic stress response increases with strain rate. It means that the cyclic behaviour of the steel is rate-dependant, or called viscoplastic. To evaluate the effect of strain rate, an effect factor (*F*) of strain rate was proposed as Equation (1).

$$F = \sqrt{(\sigma_a^{\dot{\varepsilon}=10^{-3}} - \sigma_a^{\dot{\varepsilon}=10^{-4}})^2 + (\sigma_a^{\dot{\varepsilon}=10^{-4}} - \sigma_a^{\dot{\varepsilon}=10^{-2}})^2 + (\sigma_a^{\dot{\varepsilon}=10^{-2}} - \sigma_a^{\dot{\varepsilon}=10^{-3}})^2} \quad (1)$$

where σ means the maximum stress during a stress-strain hysteresis loop at each strain rate. Relation between the factor *F* and test temperature *T* was plotted in Fig. 2 (b). Obviously, the effect of strain rate is constant from ambient to 673 K, but it becomes more and more important at higher test temperatures ($T \geq 773$ K). Consequently, it is of primary importance to take into account the strain rate effect for usual industrial applications of hot-work tool steels.

3.2. Strain memory effect

Some experimental results of strain memory effect tests were plotted in Fig. 3. It is obvious that the steel showed the plastic strain memory effects at each test temperature, in other words, in spite of the hardness of the steel cyclic stress, the cumulated plastic strain depends on the history of cyclic loading. If strain amplitude is increased after a previous linear

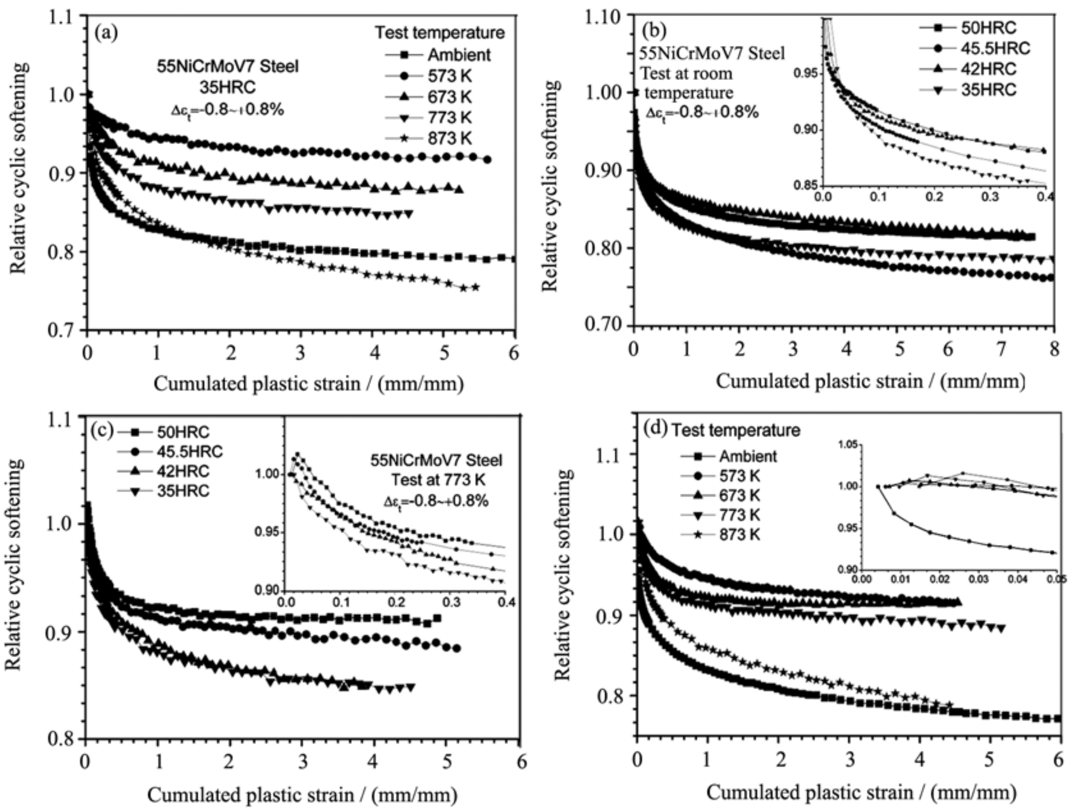

Fig. 1. **$\Delta\sigma_i/\Delta\sigma_1$-*p* curves of steel: (a) 35HRC, (b) at ambient, (c) at 773 K, (d) 45.5HRC.**

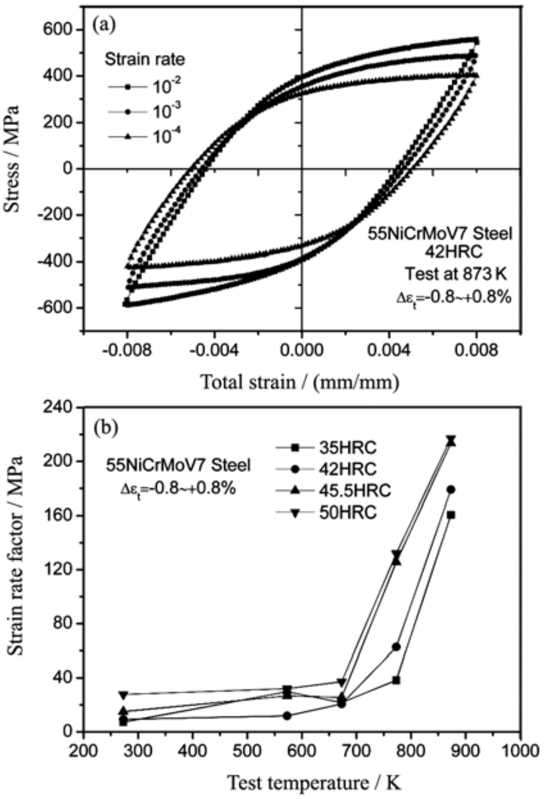

Fig. 2. (a) Stress-strain hysteresis loops at different strain rates, (b) F-T curves of the steel 55NiCrMoV7.

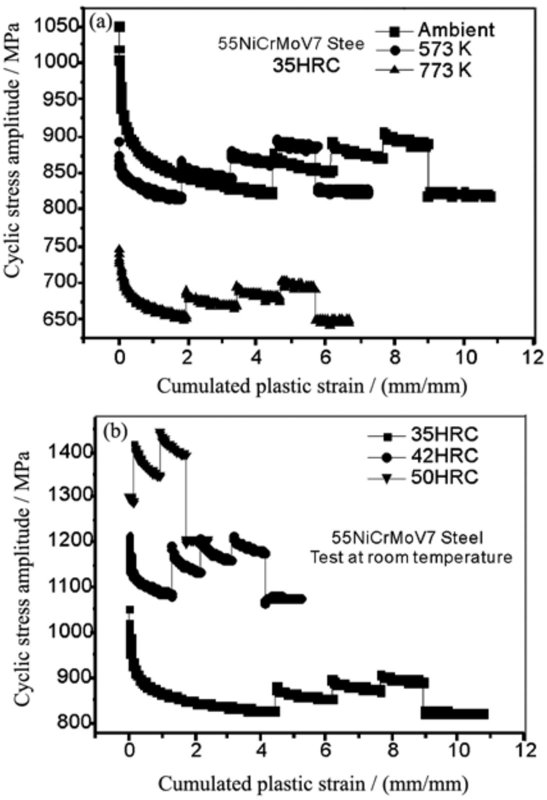

Fig. 3. Multi-levels σ-p curves of steel 55NiCrMoV7: (a) 35HRC, (b) at room temperature.

softening is achieved (for example from ± 0.6% to ± 0.7%, respectively, to ± 0.8% and ± 0.9%), a new rapid non-linear cyclic softening appears. In the opposite, if strain amplitude is decreased from ± 0.9% to ± 0.7%, softening remains linear, and moreover keeps the previous route of the linear softening curve obtained.

This effect is due to that the cyclic stress response is the function of plastic strain, i.e. the function of cumulated plastic strain. The cyclic behaviour of the steel 55NiCrMoV7 could be described by a constitutive model developed in the framework of the thermodynamics of irreversible processes. The detailed constitutive model can be found in previous paper [20]. The strain memory effect of the steel can be well reproduced by the constitutive model, as showed in Fig. 4. That means the cyclic behaviour of the steel is dependant on its strain history.

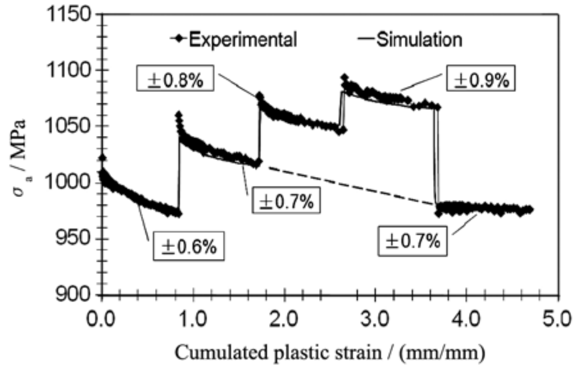

Fig. 4. Experiment-simulation comparison: stress amplitude-cumulated plastic strain for a type two test on sample 45.5HRC tested at 573 K.

4. Conclusion

The steel 55NiCrMoV7 represents cyclic softening behaviour which could be divided into rapid softening phase during the initial stage of LCF and following the gradual softening phase without cyclic saturation. Cyclic stress response was dependant on strain rate. The effect of strain rate becomes more and more important at higher test temperatures ($T \geq 773$ K). The steel showed the plastic strain memory effects at each test temperature. In despite of the hardness of the steel, cyclic stress and cumulated cyclic plastic strain depends on the history of cyclic loading. It is of primary importance to take into account the strain rate effect for usual industrial applications of hot-work tool steels.

Acknowledgement

This research was supported by the Scientific Research Foundation for the Returned Overseas Chinese Scholars, State Education Ministry of China (2004176). The Authors gratefully acknowledge the Thyssen France Company for supplying the steel investigated.

References

[1] Bernhart G., Moulinier G., Brucelle O., and Delagnes D., High temperature low cycle fatigue behaviour of a martensitic forging tool steel, *Int. J. Fatigue*, 1999, **21** (2) :179.

[2] Ryuichiro E., and Katsuaki K., Failure analysis of hot forging dies for automotive components, *Engineering Failure Analysis*, 2008, **15**: 881.

[3] Okayasu M., Sato K., Mizuno M., Hwang D.Y., and Shin D.H., Fatigue properties of ultra-fine grained dual phase ferrite/martensite low carbon steel, *Int. J. Fatigue,* 2008, **30** (8):1358.

[4] Delagnes D., Lamesle P., Mathon M.H., Mebarki N., and Levaillant C., Influence of silicon content on the precipitation of secondary carbides and fatigue properties of a 5%Cr tempered martensitic steel, *Materials Science and Engineering A, Structural Materials*, 2005, **394** (1-2): 435.

[5] Furuya Y., Matsuoka S., Shimakura S., Hanamura T., and Torizuka S., Effect of carbon and phosphorus addition on the fatigue properties of ultrafine-grained steels. *Scripta Mater,* 2005, **52**: 1163.

[6] Kimura H., Akiniwa Y., Tanaka K., Kondo J., and Ishikawa T., Effect of microstructure on fatigue crack propagation behavior in ultrafinegrained steel, *J. Mater Sci. Soc. Jpn.,* 2002, **51**: 795.

[7] Bache M.R., Jones J.P., Drew G.L., Hardy M.C., and Fox N., Environment and time dependent effects on the fatigue response of an advanced nickel based superalloy, *Int. J. Fatigue,* 2009, **31** (11-12): 1719.

[8] Zhang Z., Delagnes D., and Bernhart G., Ageing effect on cyclic plasticity of a tempered martensitic steel, *Int.J. Fatigue,* 2007, **29** (2): 336.

[9] Zhang Z.P., Qi Y.H., Delagnes D., and Bernhart G., Microstructure variation and hardness diminution during low cycle fatigue of 55NiCrMoV7 steel, *Journal of Iron and Steel Research, International*, 2007, **14** (6): 68.

[10] Kang G., and Gao Q., Uniaxial Ratcheting of SS316L Stainless Steel at High Temperature: Experiments and Simulations, [in] *Proceedings of the 18th International Conference on Structural Mechanics in Reactor Technology,* Beijing, 2005. 1006.

[11] Ishihara S., McEvily A.J., Sato M., Taniguchi K., and Goshima T., The effect of load ratio on fatigue life and crack propagation behavior of an extruded magnesium alloy, *Int. J. Fatigue,* 2009, **31** (11-12): 1788.

[12] Hong, S.G., and Lee S.-B., The tensile and low-cycle fatigue behavior of cold worked 316L stainless steel: influence of dynamic strain aging*, Int .J. Fatigue*, 2004, **26**: 899.

[13] Velay V., Bernhart G., and Penazzi L., Cyclic behavior modeling of a tempered martensitic hot work tool steel, *International Journal of Plasticity*, 2006, **22** (3): 459.

[14] Huang Z.Y., Wagner D., Bathias C., and Chaboche J.L., Cumulative fatigue damage in low cycle fatigue and gigacycle fatigue for low carbon-manganese steel, *Int. J. Fatigue*, 2011, **33** (2): 115.

[15] Kobayashi K., Yamaguchi K., Hayakawa M., and Kimura M., High-temperature fatigue properties of austenitic superalloys 718, A286 and 304L, *Int.J. Fatigue*, 2008, **30**: 1978.

[16] Dafalias Y.F., Kourousis K.I., and Saridis G.J., Multiplicative AF kinematic hardening in plasticity, *Int. J. Solid Structures,* 2008, **45**: 2861.

[17] Humayun Kabir S.M., Yeo T.I., and Kim S.H., Characterization of material parameters, [in] *Proceedings of the World Congress on Engineering,* London, 2009.

[18] Yoon S., Hong S., and Lee S., Phenomenological description of cyclic deformation using the overlay model, *Material science and engineering*, 2004, **A364**: 17.

[19] Zhang Z., Delagnes D., and Bernhart G., Anisothermal cyclic plasticity modelling of martensitic steels, *International Journal of Fatigue*, 2002, **24** (6): 635.

[20] Zhang Z., Delagnes D., and Bernhart G., Cyclic behaviour constitutive modeling of a tempered martensitic steel including ageing effect, *Int. J. Fatigue*, 2008, **30** (4): 706.