International Journal of Fatigue 87 (2016) 192–202

Contents lists available at ScienceDirect

International Journal of Fatigue

journal homepage: www.elsevier.com/locate/ijfatigue

Micromechanical finite element modelling of thermo-mechanical fatigue for P91 steels

Dong-Feng Li [a,b], Richard A. Barrett [b], Padraic E. O'Donoghue [c], Chris J. Hyde [d], Noel P. O'Dowd [e,1], Sean B. Leen [b,*,1]

[a] Shenzhen Graduate School, Harbin Institute of Technology, Shenzhen 518055, China
[b] Mechanical Engineering, College of Engineering and Informatics, NUI Galway, Ireland
[c] Civil Engineering, College of Engineering and Informatics, NUI Galway, Ireland
[d] Department of Mechanical, Materials and Manufacturing Engineering, University of Nottingham, Nottingham NG7 2RD, UK
[e] Department of Mechanical, Aeronautical and Biomedical Engineering, Materials and Surface Science Institute, University of Limerick, Ireland

ARTICLE INFO

Article history:
Received 14 August 2015
Received in revised form 24 November 2015
Accepted 25 November 2015
Available online 21 January 2016

Keywords:
Tempered martensite ferritic steels
Thermo-mechanical fatigue
Crystal plasticity
Fatigue crack initiation
Finite element

ABSTRACT

In this paper, the cyclic plasticity and fatigue crack initiation behaviour of a tempered martensite ferritic steel under thermo-mechanical fatigue conditions is examined by means of micromechanical finite element modelling. The crystal plasticity-based model explicitly reflects the microstructure of the material, measured by electronic backscatter diffraction. The predicted cyclic thermo-mechanical response agrees well with experiments under both in-phase and out-of-phase conditions. A thermo-mechanical fatigue indicator parameter, with stress triaxiality and temperature taken into account, is developed to predict fatigue crack initiation. In the fatigue crack initiation simulation, the out-of-phase thermo-mechanical response is identified to be more dangerous than in-phase response, which is consistent with experimental failure data. It is shown that the behaviour of thermo-mechanical fatigue can be effectively predicted at the microstructural level and this can lead to a more accurate assessment procedure for power plant components.

1. Introduction

In the past decade, the development of microstructural-sensitive modelling techniques has improved the understanding of mechanisms of material degradation in fatigue with the development of procedures to accurately assess structural integrity for cyclically-loaded materials and structural components [1–3]. The present study focuses on P91 steel (containing 9% Cr, 1% Mo and the balance primarily Fe), which is a widely used power plant steel. Under the operating conditions of flexible power plants, the relevant components typically experience both cyclic mechanical and thermal loads (e.g. during start-up attemperation cycles [4,5]) leading potentially to thermo-mechanical fatigue (TMF) failure. However, in the design process for current materials and structures, TMF behaviour is not typically accounted for.

The cyclic plasticity and fatigue crack initiation (FCI) behaviour of P91 is examined here, focusing on accurate microstructure-based finite element (FE) modelling. For P91 and other similar power plant steels, isothermal fatigue (IF) studies at elevated temperature [6–16] have been extensively carried out. In these studies, considerable cyclic softening has been observed which results in the loss of material strength and this softening has been revealed to be associated with reduction of dislocation density and microstructural recovery at the sub-grain level. Limited studies [4,5,17] have focused on TMF response and phenomenological continuum models have been mainly used. In recent decades, microstructure-based finite element simulations [18–33] have been developed to study the fatigue response in metals, where the constitutive response at crystallographic level is typically represented by crystal plasticity theory. For the monotonic response of P91 and other high-chromium tempered martensite ferritic steels, crystal plasticity-based FE models [34–40] have been developed with focuses on simulating microscale inelastic deformation and failure. Recently, length-scale dependent crystal plasticity models [39,33] have been developed and extended for P91 steel to account for the precipitate size effect on FCI under isothermal conditions. However, to our knowledge, microstructure-based modelling of

* Corresponding author. Tel.: +353 (0)91 495955; fax: +353 (0)91 563991.
E-mail addresses: lidongfeng@hitsz.edu.cn (D.-F. Li), richard.barrett@nuigalway.ie (R.A. Barrett), padraic.odonoghue@nuigalway.ie (P.E. O'Donoghue), Christopher.Hyde@nottingham.ac.uk (C.J. Hyde), noel.odowd@ul.ie (N.P. O'Dowd), sean.leen@nuigalway.ie (S.B. Leen).
[1] Joint senior author.

http://dx.doi.org/10.1016/j.ijfatigue.2015.11.025
0142-1123/© 2015 Elsevier Ltd. All rights reserved.

TMF behaviour in P91 steels has not yet been performed. This is necessary in quantifying the fatigue mechanisms in current power plant components under intermittent thermo-mechanical loading conditions and optimising the key material parameters for next generation power plant. As the fatigue failure mechanisms in terms of formation and development of persistent slip bands [2] are associated with the microstructure, the present work presents such a micromechanical FE model to explicitly and accurately account for the crystallographic slip based inelastic deformation and failure for P91 steels.

The objectives of the present paper are as follows: (i) Develop a microstructure-based FE model to simulate cyclic plasticity behaviour for P91 steels and compare the cyclic thermo-mechanical response with experiments; (ii) Examine the microstructure-sensitive TMF failure behaviour, in terms of sites and number of cycles to fatigue crack initiation, based on a specific scale-consistent fatigue criterion.

2. Experiment

To characterise the TMF behaviour of P91 steel, a program of in-phase (TMF-IP) and out-of-phase (TMF-OP) TMF tests have been carried out in the 400 °C to 600 °C temperature range [41]. The TMF setup is shown in Fig. 1a. The mechanical strain-temperature loading histories are illustrated schematically in Fig. 1b and c, with TMF tests conducted at strain-ranges of 1.0%, 0.8% and 0.6%, with strain-rates of $3.3 \times 10^{-4}\ s^{-1}$ and $2.5 \times 10^{-4}\ s^{-1}$. The cyclic evolution of maximum tensile and compressive stress for sample (typical) TMF-IP and TMF-OP tests are presented in Fig. 2a, showing considerable cyclic softening for all test cases. Significant asymmetry of stress is observed with a higher maximum tensile stress for TMF-OP cases, due to the maximum strain coinciding with minimum temperature (Fig. 1c), giving a stronger response under the strain-controlled conditions. A comparison of the experimentally observed TMF maximum tensile stress with isothermal fatigue (IF) data at 400 °C and 600 °C is presented in Fig. 2b. The most significant effect of plastic-strain induced recovery (softening) is observed for IF behaviour at 600 °C. The experimental strain-life results in the 400 °C to 600 °C temperature range, for IF, TMF-IP and TMF-OP test conditions, are presented in Fig. 3. Although similar levels of recovery

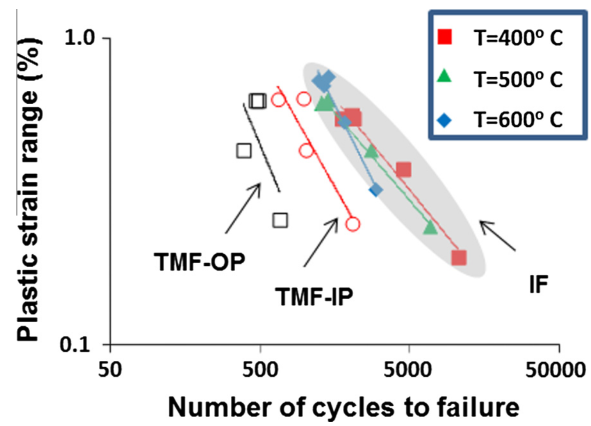

Fig. 3. Fatigue life data for P91 steels under both TMF and IF conditions.

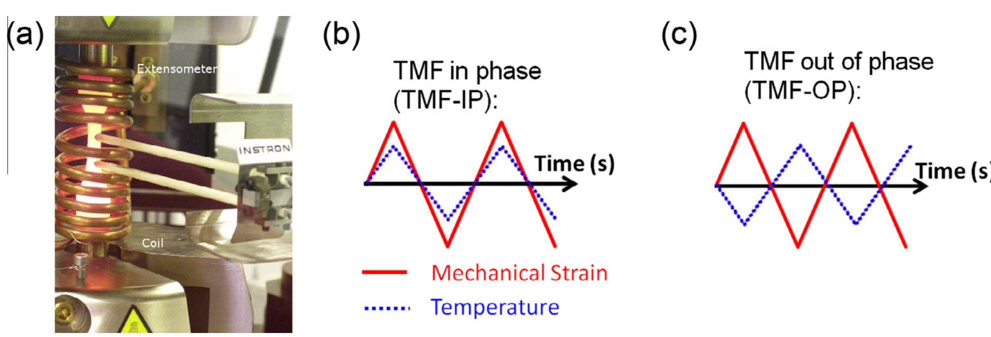

Fig. 1. Illustration of TMF test for P91 steels with (a) TMF testing setup, (b) TMF in-phase (TMF-IP) and (c) TMF out-of-phase (TMF-OP).

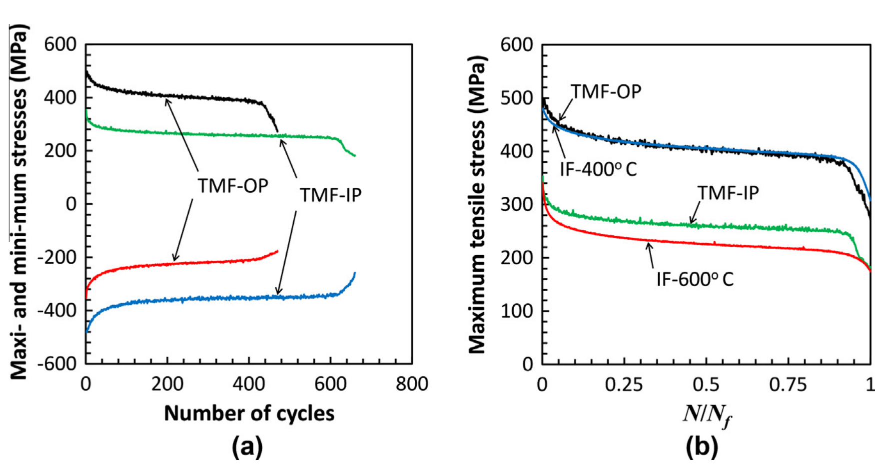

Fig. 2. TMF data for P91 steels with (a) maximum and minimum stresses vs number of cycles and (b) comparison of maximum tensile stress data for both TMF and IF.