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Multiaxial thermomechanical creep-fatigue analysis of heat-resistant steels with varying chromium contents

P. Wang [a,*], L. Cui [b], A. Scholz [a], S. Linn [a], M. Oechsner [a]

[a] Institut für Werkstoffkunde (IfW), Technische Universität Darmstadt, Grafenstrasse 2, 64283 Darmstadt, Germany
[b] IfW Darmstadt, Since July 2011 School of Mechanical Engineering, Xi'an Shiyou University, Dianzi Erlu 18, 710065 Xi'an, Shaanxi, China

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ABSTRACT

Steels with varying chromium contents are widely used in steam turbine components and have been introduced steadily in the last decades. The initial aim in the development of such steels is to achieve high performance in creep resistance. Due to the fluctuations of electrical power demand nowadays, power plants are increasingly forced to run at varying utilization levels, which can shift the critical load to the fatigue domain by superimposed creep on the heated surface of components. In the current paper, the creep fatigue behavior of 1%-, 2%- and 10%Cr steels under multiaxial loading is described. The experimental investigation was conducted on steels of the types 1Cr–1Mo–Ni–V, 2Cr–1Mo–W–V and 10Cr–1Mo–1 W–V–Nb–N as representative samples for each of the three steel grades. The experimental database consists of uniaxial as well as biaxial creep fatigue experiments which were conducted on a biaxial cruciform testing machine. Of special interest was a lifetime comparison of experiments under thermomechanical and isothermal loading at the maximum application temperature. A unified viscoplastic constitutive material model with an incorporated damage variable was applied for lifetime assessment. Finally, metallographic investigations contribute to a better knowledge of the evolution of damage and its modeling. The investigation shows slightly different effects on lifetime, dependent on the three steel grades.

1. Introduction

Due to the need for flexibility in satisfying electrical power demand nowadays, coal-fired power plants are increasingly forced to run at varying utilization levels. The temperature transients during startup and shutdown cause strain cycling with variable thermal stresses on the heated surfaces of turbine components. In steam turbines, turbine shafts belong to those components most related to safety; thus, particular attention should be paid to the lifetime assessment. Steels with various chromium contents are used for the manufacturing of steam turbine shafts and have been improved constantly in the last decades. The experimental investigation of this paper was conducted for steels of the types 1Cr–1Mo–Ni–V (German grade 28CrMoNiV4-9), 2Cr–1Mo–W–V (German grade 23CrMoNiWV8-8) and 10Cr–1Mo–1W–V–Nb (German grade X12CrMoWVNbN10-1-1) as representative for each of the three steel grades.

The initial aim in the development of these steels is primarily to improve their high performance in creep resistance. The variable loading conditions can shift the critical load to the fatigue domain by superimposed creep on the heated surface of components. Traditionally, creep-fatigue life has been assessed using the results of isothermal uniaxial tests conducted at (or close to) the peak operating temperature [1–5]. As one of the state-of-the-art creep-fatigue assessment procedures, comparison of crack initiation and propagation behavior under TMF (thermomechanical fatigue) and isothermal loading conditions on a modern 10%Cr steel was carried out in [6]. A significant lifetime reduction was observed on TMF loading compared to isothermal loading under the same mechanical strain cycle. However, lifetime behavior under multiaxial TMF conditions, especially a direct comparison of damage evolution under uniaxial/multiaxial and isothermal/TMF loading, is absent. In the current paper, the creep fatigue behavior of the three steels under multiaxial and TMF loading was investigated. Metallographic examinations have been employed to characterize the associated thermal fatigue damage mechanisms. Nonlinear finite-element calculations were performed in order to determine the stress–strain behavior under multiaxial TMF loading conditions.

* Corresponding author.
E-mail address: wp168@hotmail.com (P. Wang).

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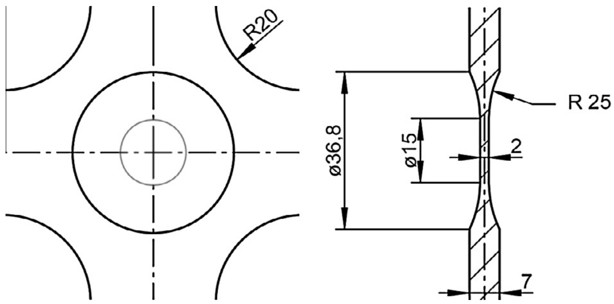

Fig. 1. Cruciform specimen used for biaxial creep fatigue experiments.

2. Experimental

2.1. Materials

The forged steel 28CrMoNiV4-9 belongs to the class of 1%Cr steels which have been used for steam turbine components in fossil power plants (plants operating at >22 MPa at 538–565 °C) since the 1960s. In addition to exhibiting decreasing mechanical strength with increasing temperature, the material provides insufficient corrosion resistance at temperatures higher than 550 °C because of the relatively low chromium content. The heat resistant steel 23CrMoNiWV8-8 was originally developed for the production of steam turbine shafts from one-piece, so-called monoblock, shafts. Due to a low thermal expansion coefficient and sufficient thermal conductivity, the investigated steel is suitable for larger forging pieces. The material reaches its limits when constructively higher strengths than the yield strength are necessary or the operating temperature is above 565 °C. In modern supercritical fossil power plants (main steam temperatures of 580–600 °C and pressures of 24–35 MPa), modern 9–12%Cr ferritic–martensitic steels are utilized. The investigated 10%Cr steel of the type X12CrMoWVNbN10-1-1 was developed in European COST Material Programs [7]. It is used for rotor shafts which are designed for operating temperatures up to 600 °C.

2.2. Experimental details

Uniaxial experiments were conducted on cylindrical specimens. They were performed on a servo-hydraulic testing machine. Total strain was controlled by the use of a side-contact extensometer. Additionally, biaxial experiments were performed on a biaxial cruciform testing system [8]. The cruciform specimen (Fig. 1) was designed by finite element analysis (FEA) in order to achieve a uniform stress distribution in the gauge section. Total strain control was performed by the use of a cruciform side-contact biaxial extensometer. Details of specimens and experimental setup are given in [8].

The testing program comprises "service-type" [9] and "service-like" [10,11] experiments. The temperature profile, strain profile and material response of a strain-controlled service-type loading cycle are illustrated in Fig. 2a–c. It is characterized by a compressive strain hold phase 1 simulating start-up conditions, a zero strain hold phase 2 approximating temperature equi-balance during constant loading, a tensile strain hold phase 3 simulating shut-down conditions and an additional zero strain hold phase 4 which characterizes zero loading condition. The sum of the four hold phases is 1.0 h for the conducted uniaxial and biaxial "service-type" tests. The strain rate is 0.00001/s. The "service-type" tests were carried out either under a TMF temperature profile or an isothermal temperature profile. In a TMF "service-type" temperature profile, the temperature rises from its minimum to maximum during hold time 1 and decreases from maximum to minimum during hold time 3 (Fig. 2a). The temperature of an isothermal profile remains constant at the maximum of the

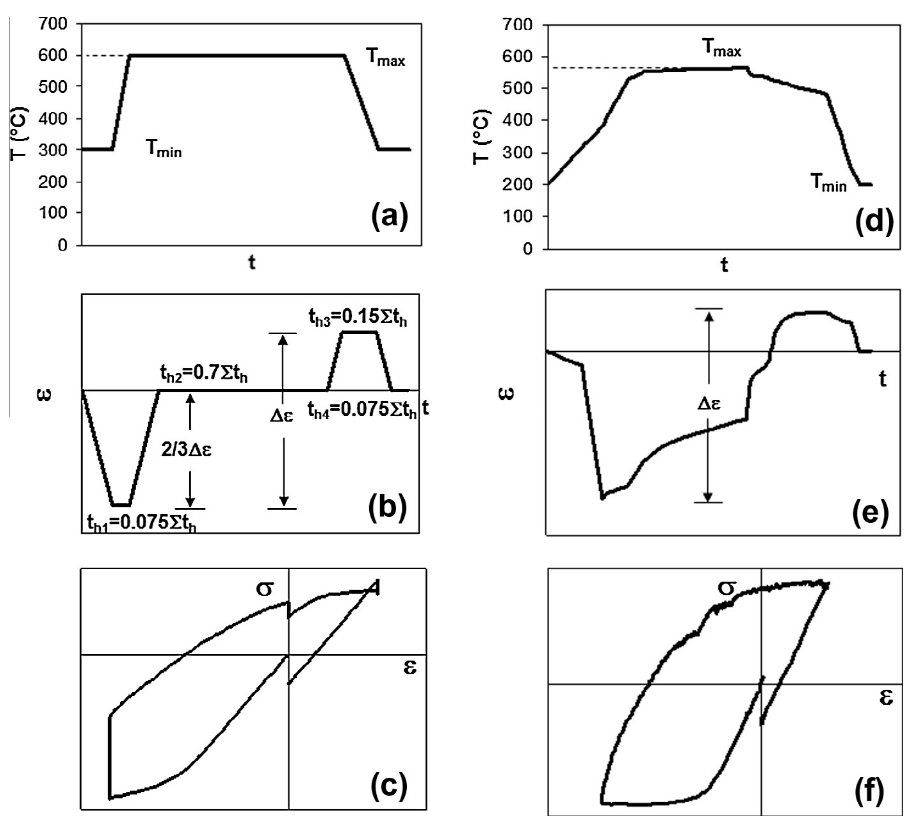

Fig. 2. Single-stage service-type [9] temperature cycle (a), strain cycle (b), corresponding hysteresis loop (c), service-like [10,11] temperature cycle (d), strain cycle (e) and corresponding hysteresis loop (f), both representing cold start cycle, sum of hold times $\sum t_h = t_{h1} + t_{h2} + t_{h3} + t_{h4}$. For more details refer to [6,8,9,13].